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OBSERVATIONS OF THE 1985 BREAKUP IN THE ATHABASCA RIVER BASIN UPSTREAM OF FORT McMURRAY, ALBERTA

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OBSERVATIONS OF THE 1985 BREAKUP
IN THE ATHABASCA RIVER BASIN
UPSTREAM OF FORT McMURRAY, ALBERTA

86-16

BY

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This report is a publication of the Alberta Co-operative Research Program in Transportation and Surface Water Engineering, participants of which are the Civil Engineering Department, Alberta Research Council; Alberta Environment; Alberta Transportation; and the Department of Civil Engineering, University of Alberta.

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ABSTRACT

This report summarizes the 1985 breakup observations on the Little Paddle, Paddle, Pembina, and Athabasca Rivers. A large jam which formed on the Athābasca River upstream of Mountain Rapids is also documented.

With a snow pack exhibiting a water equivalent of 106 mm being evident in late winter, there was a potential for significant runoff and high spring water levels. However, the long drawn out melt period resulted in relatively low snow melt runoff. Breakup on the Little Paddle River first occurred on March 10, and by March 17 the river was completely free of ice. The Paddle River at Barrhead followed on April 2, and the Pembina River at Jarvie became ice free on April 12. The Pembina River, upstream of Fawcett, appeared to break up in an overmature state. At Athabasca, the Athabasca River broke up on April 12 after about six days of activity in the reach between there and the mouth of the Pembina River. On April 14, the reach between Rapides du Joli Fou and Mountain Rapids broke up due to an ice run which originated downstream of the former. This resulted in the formation of a jam at a location upstream of Mountain Rapids. This jam ultimately melted in place sometime after April 18. The ice downstream of Mountain Rapids went out on April 18. The run past Fort McMurray peaked at an elevation of 243.5 m at the mouth of the Clearwater River. No significant jamming occurred.

The jam which formed upstream at Mountain Rapids achieved a length of 14 km, a maximum height of 7.3 m and remained in place for at least seven days. Measurements and calculations showed that the discharge responsible for the maximum height was about 1400 m^3/s. The jam was about 4.3 m thick and its Manning's roughness was 0.063. The dimensionless coefficient of internal fraction was computed to be 1.8.

ACKNOWLEDGEMENTS

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T. Ridgway, B. Trevor, and R. Evanson of the Civil Engineering Department, Alberta Research Council performed most of the field work in surveying the documented jam. Pearl S. Grey typed the final manuscript. R. A. Harrington and M. Quazi reviewed the final draft of the report.

TABLE OF CONTENTS

Page

ABSTRACT.......... i
ACKNOWLEDGEMENTS.......... ii
TABLE OF CONTENTS.......... iii
LIST OF FIGURES.......... iv
LIST OF TABLES.......... x

INTRODUCTION.......... 1

FREEZE-UP AT FORT McMURRAY.......... 6

WINTER METEOROLOGIC CONDITIONS AND ICE CHARACTERISTICS.......... 9

BREAKUP OBERVATIONS.......... 13
- Little Paddle River.......... 14
- Paddle River.......... 18
- Pembina River.......... 24
- Athabasca River.......... 29

ICE JAM DOCUMENTATION.......... 52
- Physical Characteristics.......... 52
- Discharge Estimates.......... 62
- Hydraulic Characteristics and Stability Analysis.......... 66

SUMMARY AND CONCLUSIONS.......... 69
- Breakup Observations.......... 69
- Experimental Ice Station.......... 71
- Ice Jam Characteristics.......... 72

REFERENCES.......... 73

LIST OF FIGURES

Page

Figure 1. Location plan.................................... 2

Figure 2. Fort McMurray study area.............................. 5

Figure 3. Freeze-up gauge heights at WSC Gauge #07DA001, October and November 1984............................. 7

Figure 4. Meteorologic and hydraulic characteristics during freeze-up at WSC Gauge #07DA001, October and November 1984.................................... 8

Figure 5. Ice thickness measurement locations on the Athabasca River in the vicinity of Fort McMurray, 1984-85........ 12

Figure 6. Daily maximum and minimum air temperatures at three locations in the Athabasca River basin, March and April 1985.. 15

Figure 7. Degree days of melt and snow pack reduction at the Twin Lakes snow pillow, March and April 1985........... 16

Figure 8. Stages at selected WSC gauging stations on the Little Paddle, Paddle, and Pembina Rivers, March and April 1985...................................... 18

Figure 9. Open water on the Little Paddle River near Mayerthorpe, March 19, 1985...................................... 19

Figure 10. Open water on the Paddle River upstream of the confluence of the Little Paddle River, March 19, 1985.. 19

Page

Figure 11. Open water on the Paddle River downstream of the confluence of the Little Paddle River, March 19, 1985 21

Figure 12. Intact ice cover on the Paddle River upstream of bridge crossing 6 km west of Mosside, March 19, 1985 21

Figure 13. Fractured ice cover on the Paddle River upstream of bridge crossing 8 km west and 3 km south of Barrhead, March 19, 1985 22

Figure 14. Fractured ice cover and overflow on Paddle River downstream of bridge crossing at Barrhead, March 19, 1985 22

Figure 15. Fractured ice cover and overflow along the bank on the Paddle River upstream of the Barrhead bridge crossing, March 19, 1985 23

Figure 16. Intact ice cover on the Paddle River at the first bridge crossing upstream of the mouth, March 19, 1985 23

Figure 17. Open water and accumulated broken ice on the Paddle River near the sewage lagoons, downstream of Barrhead, April 1, 1985 25

Figure 18. Flow over snow-covered ice on the Pembina River upstream of the bridge crossing at Belevdere, March 19, 1985 25

Figure 19. Intact ice cover with small open areas on the Pembina River upstream of the mouth of the Paddle River, April 1, 1985 26

Page

Figure 20. Ice cover on the Pembina River downstream of the mouth of the Paddle River, April 1, 1985........... 26

Figure 21. Ice cover on the Pembina River at Rossington, April 1, 1985.. 27

Figure 22. Ice cover with considerable open water on the Pembina River at Pibroch, April 1, 1985................ 27

Figure 23. Ice cover on the Pembina River downstream of Fawcett, April 1, 1985................................. 28

Figure 24. Intact, but nearly destroyed ice cover on the Pembina River upstream of the mouth of the Paddle River, April 1, 1985.................................. 28

Figure 25. Intact ice cover with minimal leads on the Pembina River at Rossington, April 6, 1985..................... 30

Figure 26. Intact, but nearly totally destroyed (thermally) ice cover on the Pembina River at Pibroch, April 6, 1985.. 30

Figure 27. Intact ice cover on the Pembina River at Jarvie, April 6, 1985.. 31

Figure 28. Fractured and transported ice on the Pembina River at the mouth of French Creek, April 6, 1985............... 31

Figure 29. Open water on the Pembina River downstream of Fawcett, April 6, 1985................................. 32

Page

Figure 30. The toe of a 10 kilometre long jam on the Pembina River at its confluence with the Athabasca River, April 6, 1985 32

Figure 31. The progression of breakup between the mouth at the Pembina River and Suncor on the Athabasca River, April 1985 33

Figure 32. Lateral fracturing of the ice cover on the Athabasca River downstream of the mouth of the Pembina River, April 6, 1985 36

Figure 33. Leads developing along the right bank of the Athabasca River at the the Town of Athabasca, April 6, 1985 36

Figure 34. Water levels during breakup on the Athabasca River at WSC Gauge #07BE001, April 1985 38

Figure 35. Fractured and transported ice cover on the Athabasca River at the Town of Athabasca, April 11, 1985 39

Figure 36. Open water and evidence of only a minor stage increase associated with the removal of the ice cover on the Athabasca River at Smith, April 11, 1985 40

Figure 37. Peak stage at the Hwy 2 bridge crossing of the Athabasca River at Hondo, following the formation of an ice jam downstream, 15:00 hours, April 12, 1985 41

Figure 38. Intact but deteriorating ice cover on the Athabasca River near Iron Point, April 13, 1985 42

Page

Figure 39. Intact and competent ice cover on the Athabasca River downstream of Stony Rapids, April 13, 1985............. 42

Figure 40. Competent ice cover on the Athabasca River upstream of Grande Rapids, below which the channel is completely open, April 13, 1985........................ 44

Figure 41. Deteriorating cover with numerous leads and open areas on the Athabasca River at Long Rapids, April 13, 1985.. 44

Figure 42. Virtually intact ice cover on the Athabasca River downstream of Mountain Rapids, April 13, 1985.......... 45

Figure 43. Toe of an ice jam keyed into competent ice on the Athabasca River at Stony Rapids, April 13, 1985........ 45

Figure 44. Toe of running ice on the Athabasca River downstream of Cascade Rapids, 10:25 hours, April 14, 1985......... 47

Figure 45. Rapidly deteriorating ice cover on the Athabasca River downstream of Mountain Rapids, April 15, 1985.......... 47

Figure 46. Remnants of the ice run of the Athabasca River at the MacEwan Bridge, April 19, 1985......................... 48

Figure 47. Water levels on the Athabasca River during breakup at the MacEwan Bridge, April 1985......................... 49

Figure 48. Water levels during breakup on the Athabasca River at WSC Gauge #07DA001, April 1985......................... 50

Page

Figure 49. Intact but deteriorating ice cover on the Athabasca River downstream of Stony Rapids, April 17, 1985....... 51

Figure 50. Extent of the jam upstream of Mountain Rapids, April 14-16, 1985.................................... 53

Figure 51. Toe of the documented jam upstream of Mountain Rapids April 15, 1985...................................... 55

Figure 52. Rearrangement of the channel bed at the toe of the jam.. 55

Figure 53. Disturbed bed material resulting from grounding at the toe of the jam................................ 56

Figure 54. Ice level profile through the jam upstream of Mountain Rapids.. 57

Figure 55. Floe orientation within the equilibrium reach of the documented ice jam............................. 58

Figure 56. Open lead through the body of the ice jam at Cascade Rapids... 58

Figure 57. Thin ice cover, approximately one floe thick at the head of the ice jam.............................. 59

Figure 58. Shear wall in the order of 4 m in thickness upstream of the head of the ice jam.......................... 59

Figure 59. Surveyed cross sections in the vicinity of the documented ice jam.................................... 60

Figure 60. Estimates of the formative discharge of the ice jam upstream of Mountain Rapids........................... 65

LIST OF TABLES

Page

Table 1. Summary of Freeze-up Characteristics at WSC Gauge #07DA001 9

Table 2. Summary of Monthly Temperature and Precipitation at Fort McMurray, Winter 1984-85 10

Table 3. Hydraulic Characteristics at WSC Gauge #07DA001, Winter 1984 11

Table 4. Ice Thickness Measurements on the Athabasca River at the Confluence of the Clearwater River, Winter 1984-85 13

Table 5. Summary of the Open Water Hydraulic Characteristics, $Q = 820\ m^3/s$ 56

Table 6. Summary of the Geometric Characteristics of the Documented Ice Jam 62

Table 7. Trial Estimates of the Thickness and Roughness of the Documented Ice Jam 68

Table 8. Summary of Measured and Computed Ice Jam Characteristics. 69

INTRODUCTION

Fort McMurray, Alberta is situated on the Athabasca River at the confluence of the Clearwater River (figure 1 and 2). Ice jams often form downstream of Fort McMurray and sometimes cause serious flooding within the community. The most recent flood of this nature occurred in 1979 (Doyle and Andres, 1979).

At present, the forecasting of even the formation of an ice jam, let alone the time it forms and its severity, is an almost impossible task. Most of the difficulty comes from a lack of an understanding of the breakup processes, in the basin upstream, which affect the breakup mode of Fort McMurray. Previous observations (Andres and Rickert; 1984, 1985) have identified a typical progression of melt from the Little Paddle River basin, through the Paddle and Pembina Rivers, and finally down the Athabasca River. Although the rapid sections of the Athabasca River can break up independently of the system under certain conditions, there appears to be an established pattern to breakup. Unfortunately there is insufficient information to confidently establish this pattern. Hence the purpose of this report.

The information presented herein summarizes the events leading up to the 1985 breakup. Included is a brief description of the 1984 freeze-up and the 1984-85 ice characteristics at Fort McMurray. The breakup progression from the Little Paddle River basin to the Athabasca River basin at Fort McMurray is described and put into the context of the snow pack conditions and the characteristics of the spring melt. An observed ice jam on the Athabasca River upstream of Fort McMurray is described and analysed. Also, an attempt to remotely document the exact timing of breakup upstream of Fort McMurray is described and evaluated. Recommendations are also made with respect to future activities.

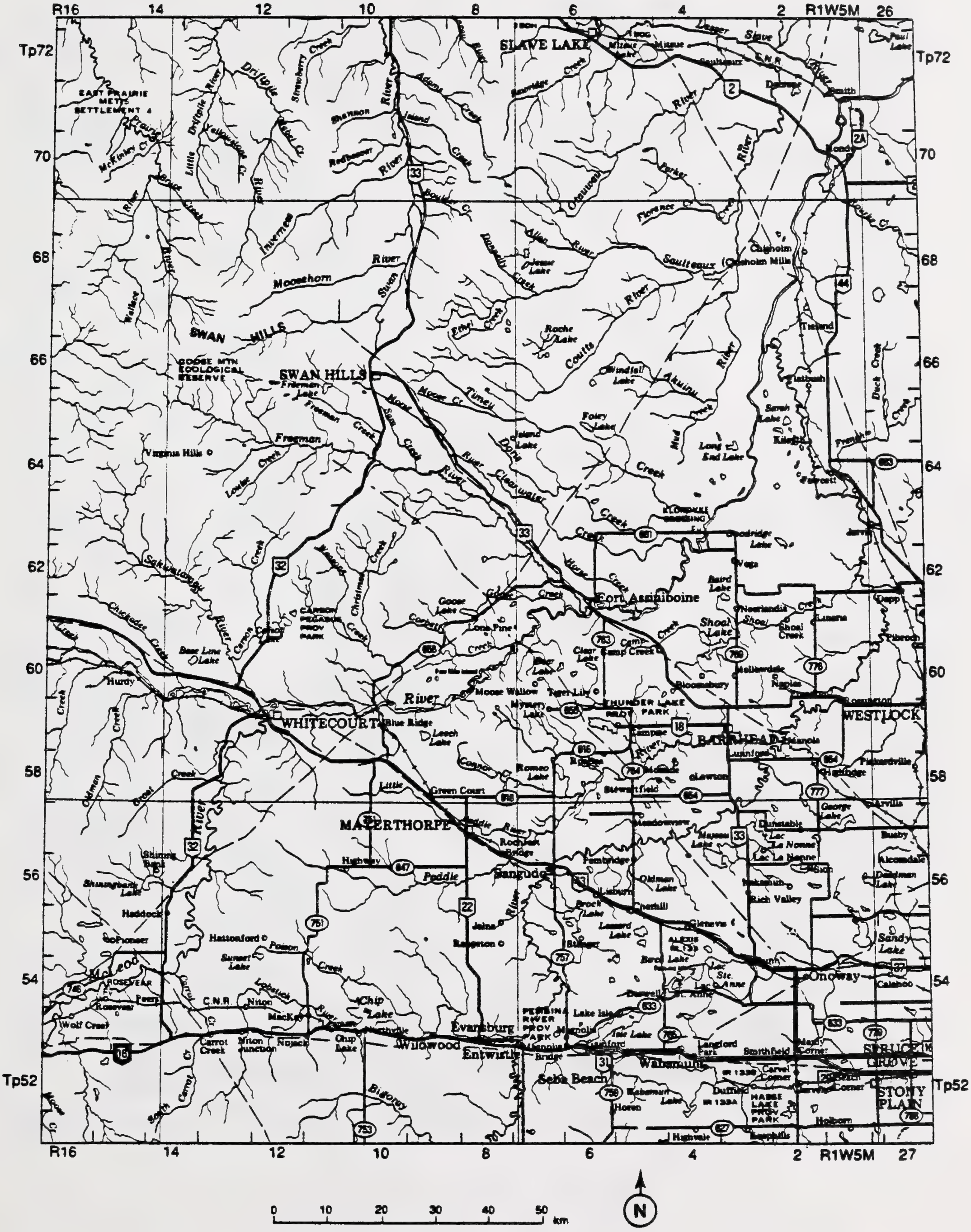

Figure 1a. Location plan

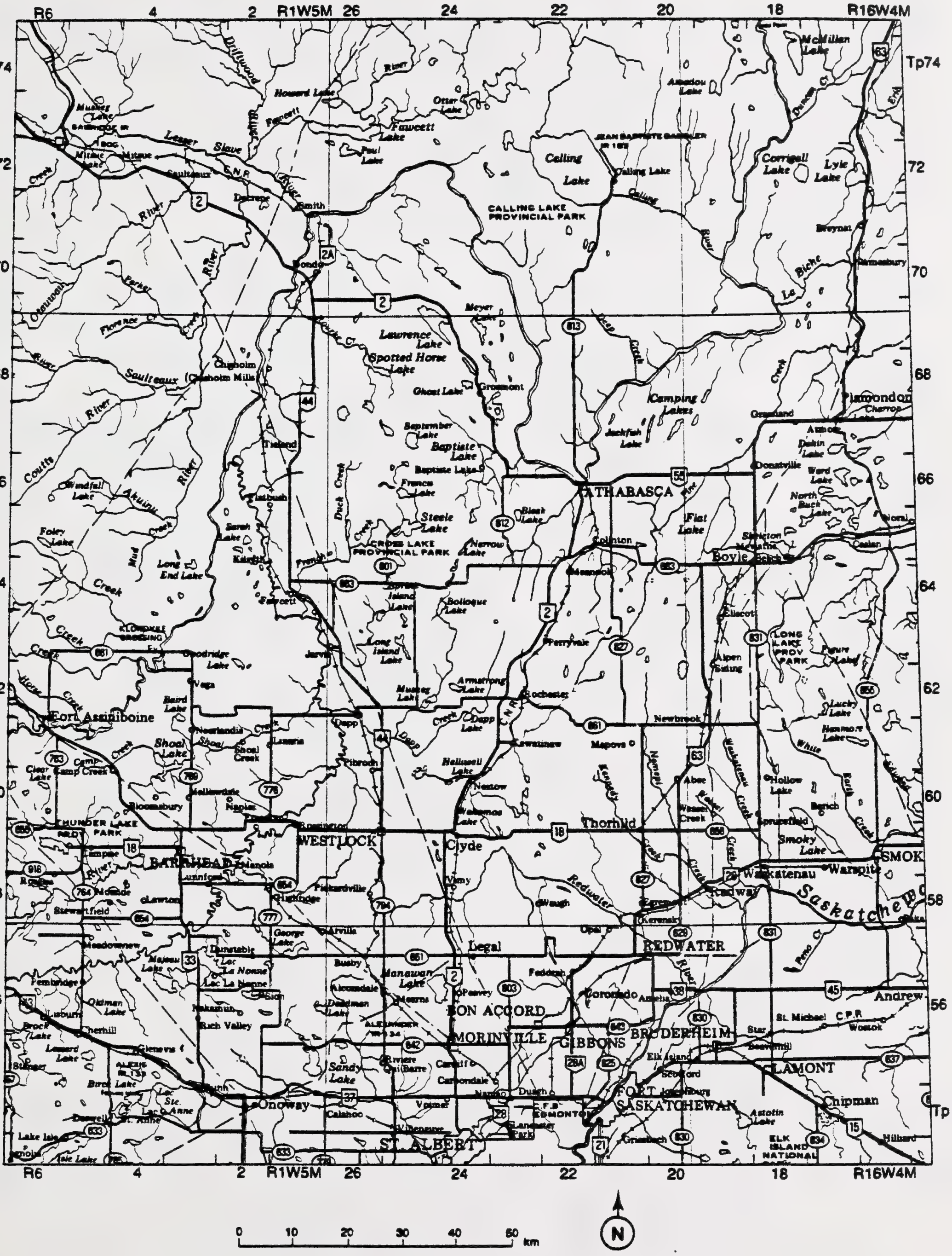

Figure 1b. Location plan

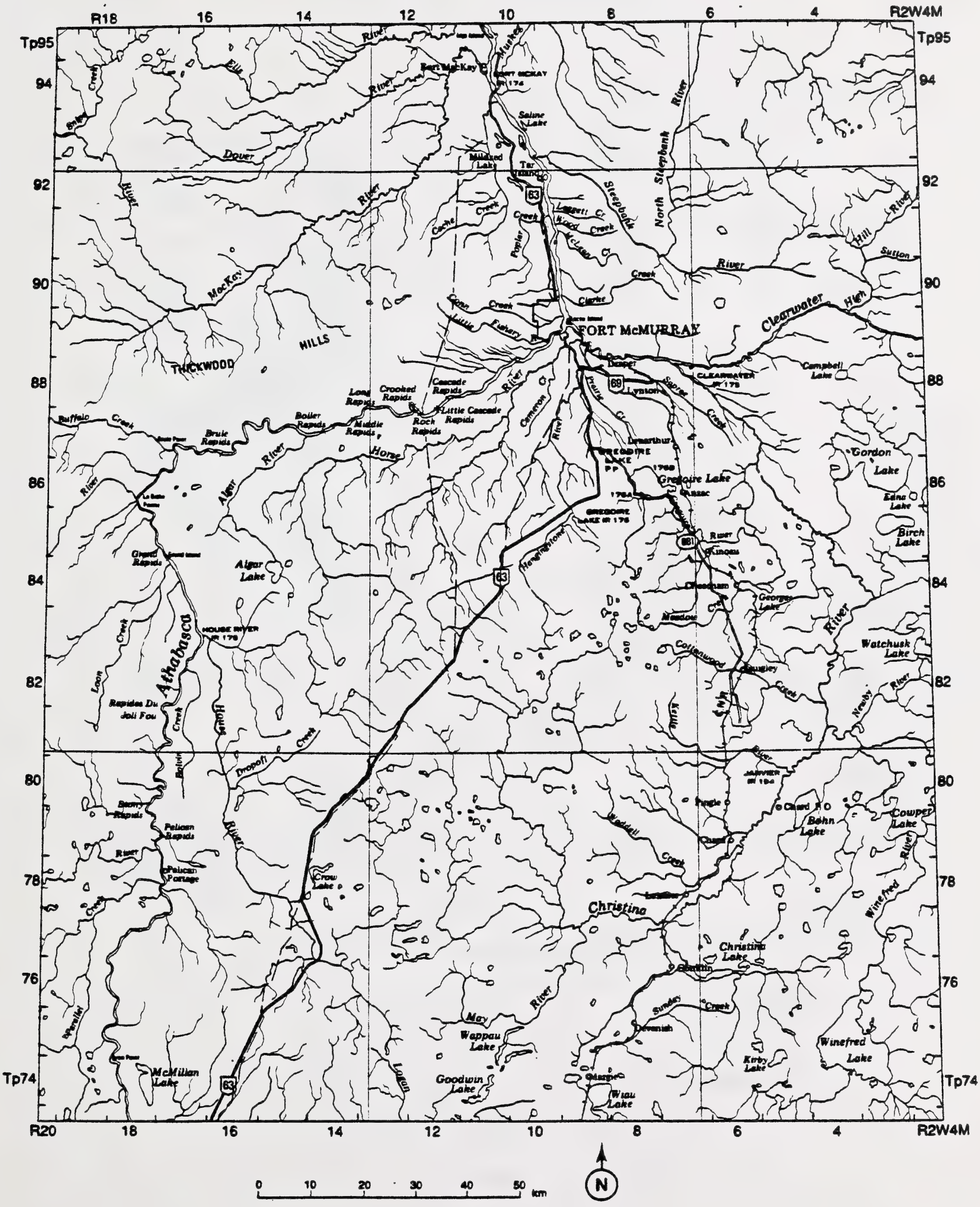

Figure 1c. Location plan

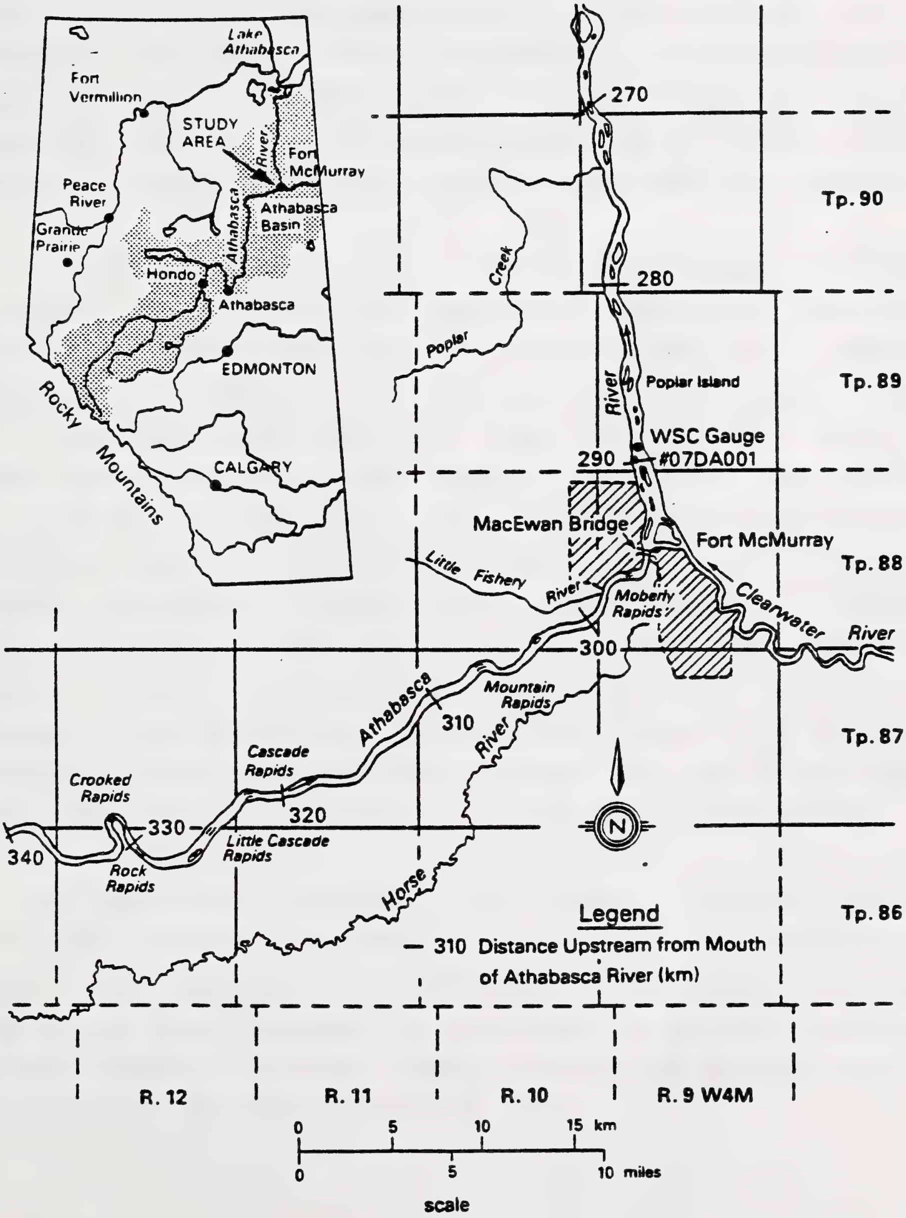

Figure 2. Fort McMurray study area

FREEZE-UP AT FORT McMURRAY

Freeze-up on the Athabasca River downstream of Fort McMurray results from the upstream progression of an ice cover by the juxtaposition of ice floes. Frazil is generated in the turbulence of the rapids upstream of Fort McMurray and forms into floes as it is carried downstream. Lodgment occurs somewhere downstream of the Water Survey of Canada (WSC) gauge and the cover progresses upstream from that point.

In 1984, a stable ice cover formed at the WSC gauge on October 29 (figure 3) after 55 C°-days of freezing, at a mean daily temperature of -15.2°C, and after seven days of sub-zero mean daily temperature (figure 4). Just prior to freeze-up, the discharge was estimated by WSC to be approximately 720 m^3/s at a gauge height of about 2.2 m. The gauge fluctuations indicate that freeze-up was slightly more complicated this year than in past years. There may have been more shoving and thickening and/or an intermittent cover may have formed prior to complete freeze-over. On the strip chart (figure 3), distinctive evidence of temporary cover formation is apparent at water elevations of 238.1 m, 239.0 m, and finally at 239.35 m at which point the cover appeared to have stabilized. Following cover formation at 12:00 hours, October 29, there was a reduction in stage when some of the flow was placed into channel storage as the ice cover progressed upstream.

An equilibrium condition at the summer discharge measurement section was achieved at a Froude number of 0.11. This relatively high Froude number suggests that hydrodynamic instability at the advancing edge of the cover governed its thickness, as opposed to mechanical instability within the cover. Table 1 compares the freeze-up statistics of the previous two years to those of 1984.

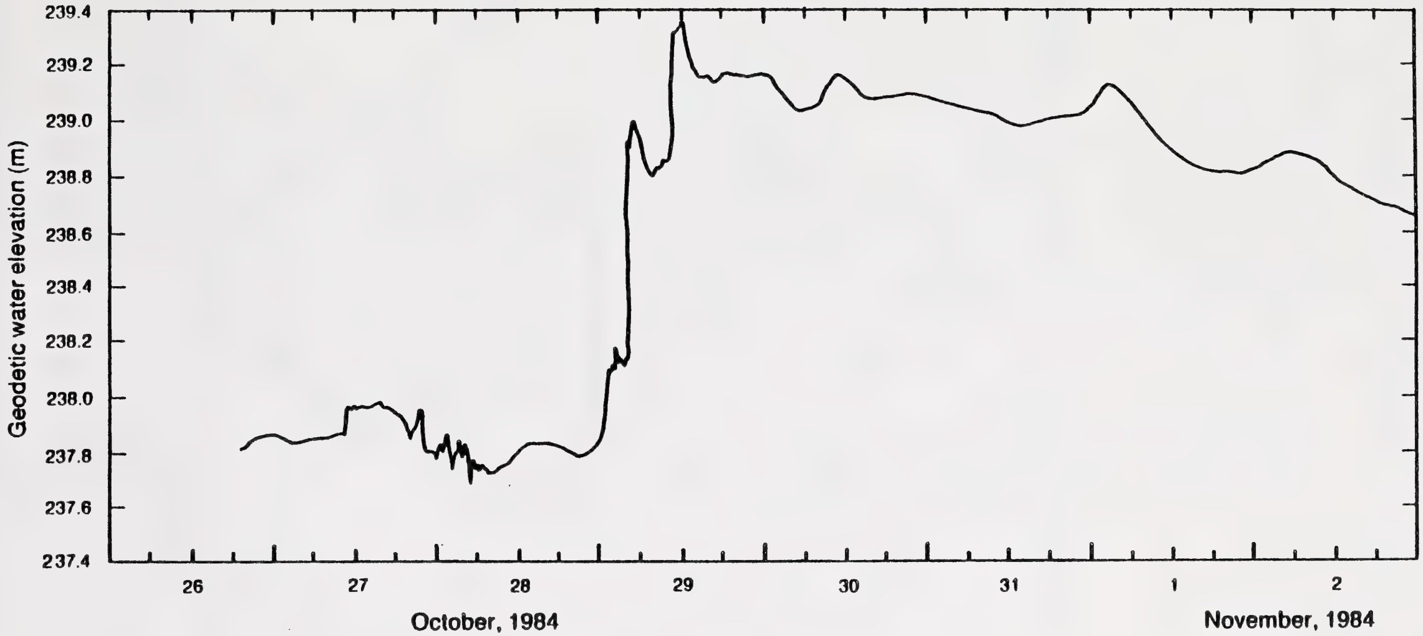

Figure 3. Freeze-up gauge heights at WSC Gauge #07DA001, October and November 1984

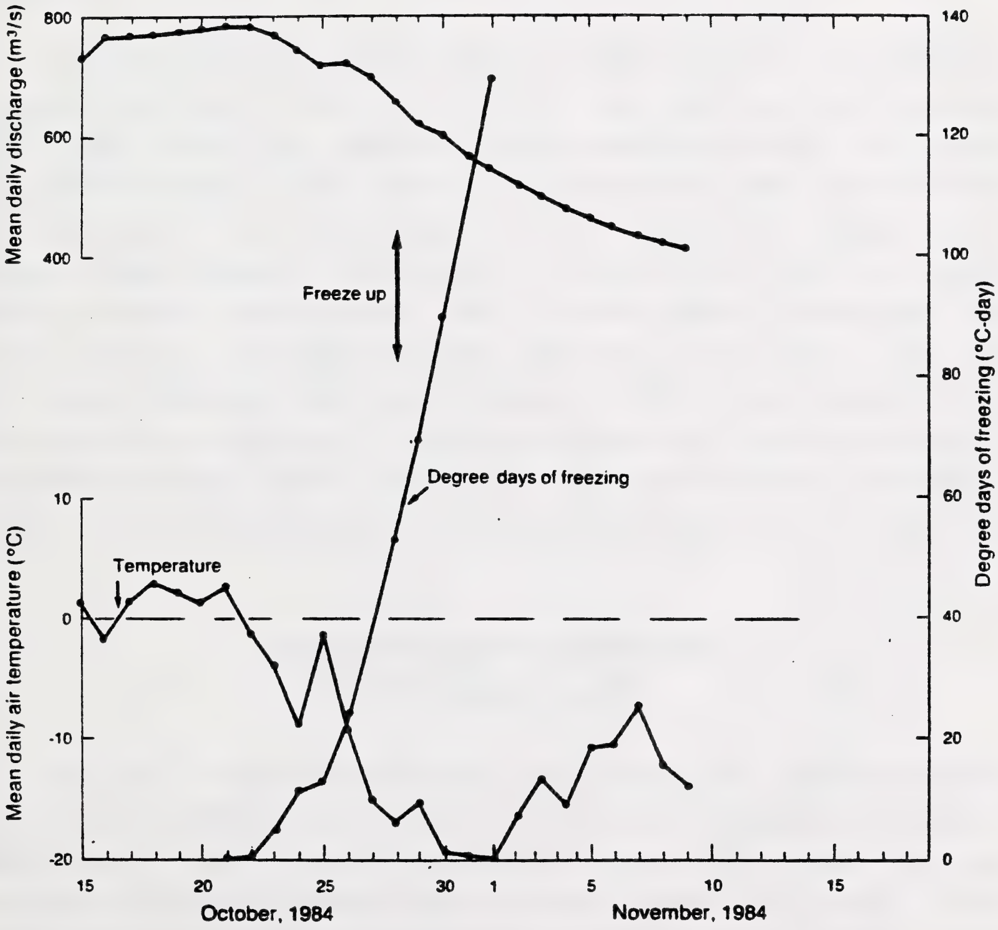

Figure 4. Meteorologic and hydraulic characteristics during freeze-up at WSC Gauge #07DA001, October and November 1984

Table 1.
Summary of Freeze-up Characteristics at WSC Gauge #07DA001

Year	1982	1983	1984
Discharge (m^3/s)	400	480	720
Peak stage (m)	3.00	2.75	3.55
Stage increase (m)	1.38	0.95	1.35
Froude number	0.08	0.11	0.11
Temperature (°C)	-8	-12	-15

In each of the years the freeze-up Froude number is high enough to suggest that frontal stability is the critical conditions which must be satisfied. It is also apparent that at temperature below -10°C, considerable freezing of the floes in the pack and/or the larger size of pans arriving at the head allows for equilibrium to be achieved at a higher Froude number. This suggests a thicker cover would be anticipated at warmer temperatures. This is borne out by considering the stage increases associated with the formation of the cover. Even for the lowest discharge, the stage increase in 1982 was the largest of all the three years considered. With the roughness not being significantly different each year (due to the similar nature of freeze-up) the higher stage increase in 1982 can only be accounted for by a thicker cover.

WINTER METEOROLOGIC CONDITIONS AND ICE CHARACTERISTICS

The mean winter temperature at Fort McMurray of -14.3°C suggests the winter of 1984-85 was "normal". The months of November, December, and February (table 2) were considerably colder than normal but the months of January and March were considerably warmer than normal. This would indicate a relatively severe winter with a mild early spring. The precipitation at Fort McMurray was about 62 percent of normal with all months exhibiting below normal precipitation, especially March, which was only 42 percent of normal.

Table 2.

Summary of Monthly Temperature and Precipitation at Fort McMurray, Winter, 1984-85

	Month				
	November	December	January	February	March
Monthly Average Maximum Daily Temperature (°C)	-8.1 (-3.5)[1]	-16.3 (-12.2)	9.0 (-16.5)	-14.0 (9.0)	3.1 (-2.2)
Monthly Average Minimum Daily Temperature (°C)	-16.4 (-12.7)	-27.5 (-21.9)	-19.7 (-27.1)	-26.7 (-21.8)	-8.5 (-16.1)
Monthly Average Mean Daily Temperature (°C)	-12.2 (-8.2)	-21.9 (-17.0)	-14.4 (-21.8)	-20.4 (-15.4)	- 2.7 (-9.2)
Total Precipitation (mm)	19.8 (25.2)	12.3 (25.0)	12.4 (22.7)	16.4 (18.8)	8.7 (20.7)

[1] bracketed values indicate normal conditions.

Ice thicknesses are available at two locations on the Athabasca River. Measurements at the new WSC winter metering section (see Andres and Rickert, 1984 for location) showed a submerged ice thickness of 0.57 m on December 13, 46 days after freeze-up. This thickness increased to 0.79 m by April 2. When compared to data from the years between 1975 and 1983 (Andres and Rickert, 1984), these thicknesses are about average. Therefore, even if it was a colder than normal winter, with below normal snow fall, the ice thicknesses are not obviously greater than normal and do not reflect the potential for a thicker ice cover.

Table 3 summarizes the ice cover characteristics at the WSC gauge. Of most interest is the change in the Manning's roughness of the ice cover. The roughness stayed relatively constant during the winter, starting at 0.023 for the first winter measurement on December 13. From then on, the roughness increased slightly to 0.029 as the discharge

decreased. On April 2, after a very warm month when one would expect considerable melting of the underside to cause an increase in roughness, the roughness instead decreased to 0.023. It is apparent that when the resistance is written in terms of Manning's formula it is more sensitive to changes in the mean depth than to changes in the configuration of the underside of the ice cover.

Table 3.

Hydraulic Characteristics at WSC Gauge #07AD001, Winter 1984-85

Date	December 13	January 14	March 14	April 2
Discharge (m^3/s)	237	193	164	255
Gauge height (m)	2.42	2.18	2.17	2.51
Area (m^2)	354	304	285	344
Top width (m)	170	150	138	135
Mean depth (m)	2.08	2.03	2.07	2.55
Solid ice thickness (m)	0.57	0.68	0.79	0.72
Composite roughness [1]	0.022	0.023	0.025	0.022
Ice cover roughness [2]	0.023	0.025	0.029	0.023

[1] computed with a channel slope of 0.23 m/km

[2] computed by the Sabaneev equation with a Manning's bed roughness of 0.021.

Personnel from the City of Fort McMurray also made ice thickness measurements at the confluence of the Clearwater River and near the MacEwan Bridge. These measurements are tabulated in table 4 and their locations are shown in figure 5. The mean ice thickness increases from 0.66 m on December 19 to 1.12 m on February 26. It then remains relatively constant (±0.1 m) until March 20. From this data it is again apparent, as noted in Andres and Rickert (1984, 1985), that the mean pre-breakup ice thickness is in the order of 1 m. This value is usually similar from year to year within a narrow range of thickness due likely to inconsistent measurement techniques rather than differences in growth rates.

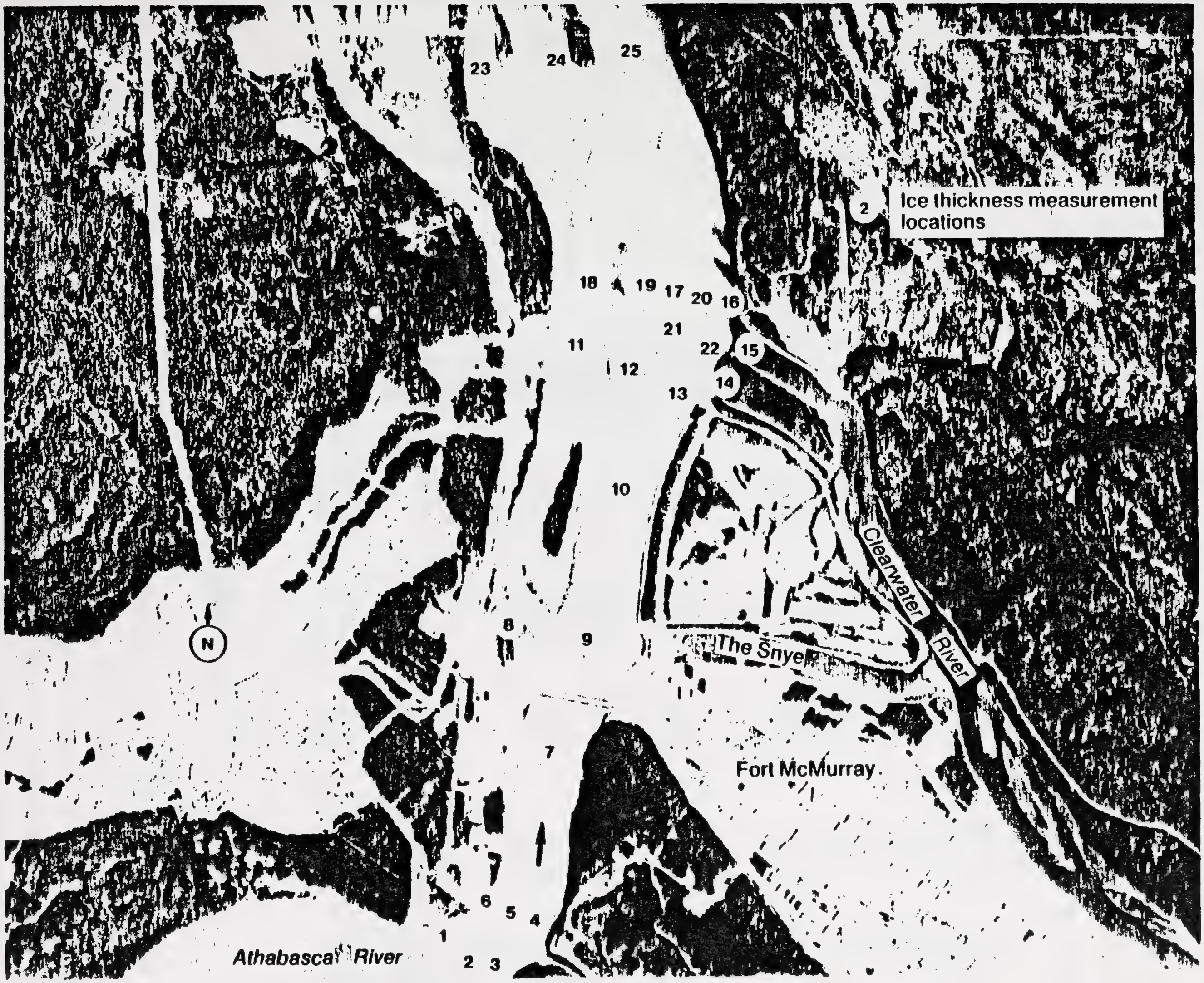

Figure 5. Ice thickness measurement locations on the Athabasca River in the vicinity of Fort McMurray, 1984-85

Table 4.

Ice Thickness Measurements on the Athabasca River at the Confluence of the Clearwater River, Winter 1984-85

Location[1]	Thickness (m)					
	Dec. 19	Jan. 22	Feb. 19	Feb. 22	Mar. 5	Mar. 20
1	-	-	1.3	1.3	1.3	1.5
2	-	-	1.2	1.3	1.2	1.5
3	-	-	0.80	0.90	0.80	0.90
4	-	-	1.2	1.3	1.1	1.4
5	0.90	0.90	1.1	1.2	1.1	1.3
6	-	-	1.4	1.2	1.4	1.3
7	-	-	1.1	1.2	1.0	1.1
8	-	0.90	1.0	1.0	1.0	-
9	-	1.1	1.2	1.3	1.1	1.5
10	0.30	0.49	0.78	0.80	0.80	1.1
11	0.46	0.65	-	-	-	-
12	0.60	0.73	1.1	1.3	1.1	1.2
13	0.60	0.78	-	-	-	-
14	0.41	0.70	0.91	1.1	1.1	1.0
15	0.36	0.60	0.76	0.70	0.70	0.70
16	0.76	0.76	-	-	-	-
17	0.61	0.74	0.99	1.2	0.90	1.1
18	0.71	0.76	0.97	1.1	0.90	1.0
19	0.70	0.71	0.85	1.2	0.75	1.0
20	0.70	0.87	0.99	1.2	1.0	1.2
21	1.0	0.75	-	-	-	-
22	0.91	0.99	-	-	-	-
23	0.91	0.80	1.0	1.1	0.90	1.0
24	0.75	0.74	1.0	1.0	0.90	0.60
25	0.48	-	0.85	1.0	0.80	0.75
Mean	0.66	0.78	0.85	1.12	0.99	1.11
Standard Deviation	0.21	0.14	0.18	0.17	0.19	0.27

[1] see figure 5

BREAKUP OBSERVATIONS

Observations of breakup were carried out on a basin-wide scale to establish the overall breakup pattern. The timing and severity of breakup was documented from the Little Paddle River, along the Paddle and Pembina Rivers and down the Athabasca River to Fort McMurray. The most intensive effort was spent on the Athabasca River because it is the most dynamic and variable of all the rivers. It spans the greatest geographic area and hence is most affected by climatic gradients.

Little Paddle River

Data on the snow pack conditions in the plains area of Alberta, which encompass these basins, are limited to one recording snow pillow located at Twin Lakes and numerous snow courses, surveyed on a monthly or semi-monthly basis (Alberta Environment, 1985). The November to March snowfall over the plains area was about 70 to 80 percent of normal. A maximum areal average water equivalent of 106 mm was recorded in late February. This value was maintained into mid-March, when 102 mm of water equivalent snow was measured, but fell to 80 mm by late March after considerable melting in the Athabasca River basin (see the melting curves in figure 6). This data, from numerous snow courses in the plains area, agrees relatively well with the data from the Twin Lakes snow pillow.

The snow water equivalent at the Twin Lakes snow pillow averaged about a constant 100 mm between March 10 and March 20 (figure 7) even though considerable melt appeared to be taking place at average mean daily temperatures of 1.6°C at Campsie. Between March 20 and April 2, there was a gradual reduction in the snow water equivalent at a rate of 3 mm/day. This melting seemed to occur even though the overall mean temperature during this period was barely above 0°C and prior to March 30, averaged -15°C. Apparently the solar radiation was sufficient to maintain the low melt rate and by April 2, the snow water equivalent at the snow pillow was reduced to about 80 mm.

During early March, even though it appears that no significant snow melt was occurring, the Little Paddle River was showing signs of activity (figure 8). Observations on March 19 indicated that the Little Paddle River was running free of ice near Mayerthorpe (figure 9) at a stage of about 1.7 m and had dropped about 0.3 m from the peak stage. There was no sign of a significant ice run and it appeared that the ice had essentially melted in place. By March 22, the stage had dropped to about 0.95 m and remained so until March 31, when the stage began to increase. This trend of increasing stage first became apparent two days prior to the beginning of significant melt at the Twin Lakes snow

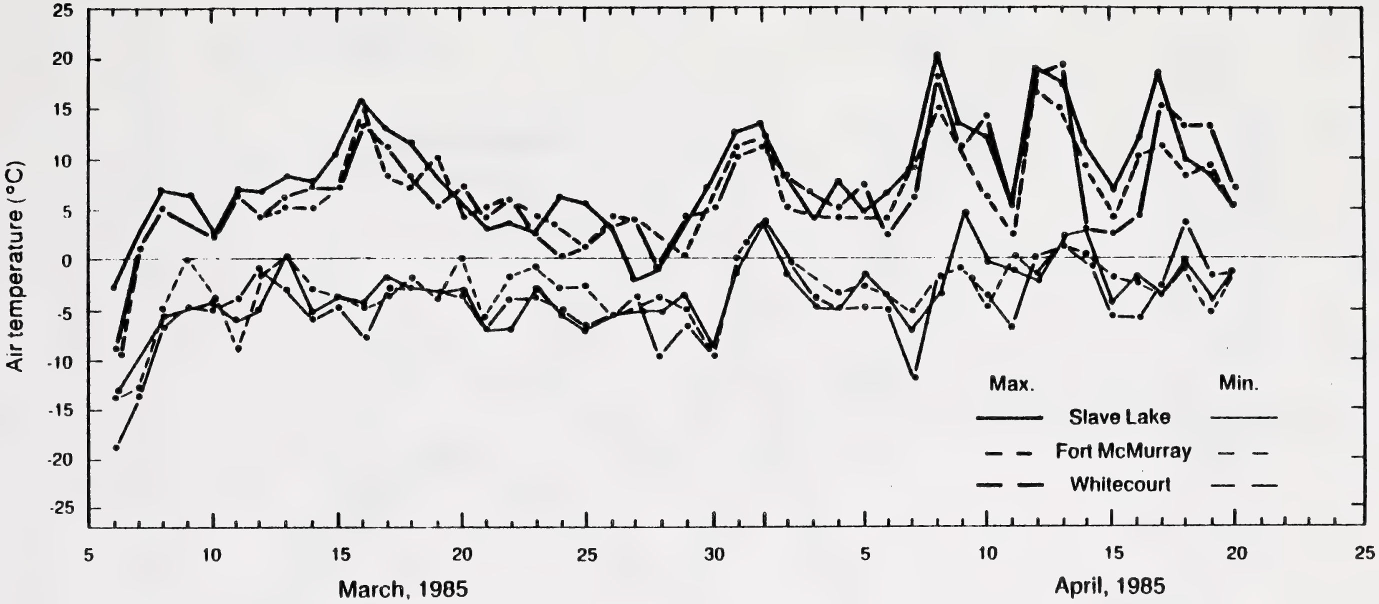

Figure 6. Daily maximum and minimum air temperatures at three locations in the Athabasca River basin, March and April, 1985

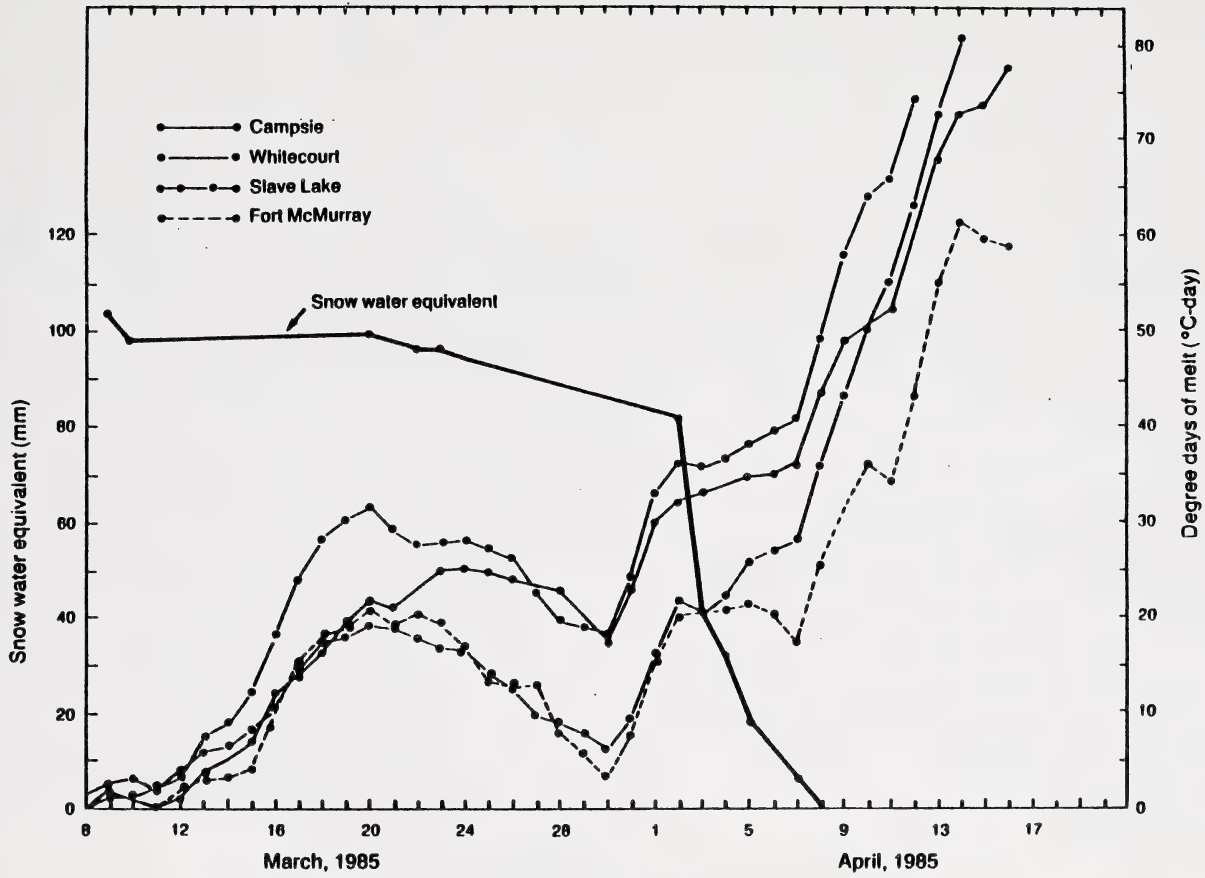

Figure 7. Degree days of melt and snow pack reduction at the Twin Lakes snow pillow, March and April, 1985

Figure 8. Stages at selected WSC gauging stations on the Little Paddle, Paddle, and Pembina Rivers, March and April 1985

pillow. Subsequently, the flow on the Little Paddle River peaked on April 2, precisely the day when the snow melt began to accelerate at the snow pillow. This may be explained by the fact that 7.8 mm of precipitation, which fell as snow, at Whitecourt on March 28 may have triggered this event. However this snow fall was not recorded at the snow pillow, nor at Campsie, where the observers comments indicate only "variable cloud".

The start of significant snow melt at the Twin Lakes snow pillow on April 2 followed three days of warming at Campsie. With continuing warming, at average mean daily temperatures in the order of 3°C, the entire snow pack was removed by April 8. This was achieved at a melt rate of about 13 mm/day.

Paddle River

The Paddle River responded in a similar fashion to that of the Little Paddle River. Prior to March 10, the stage at Barrhead was in the order of 0.8 m. On that day there was a sharp increase in stage of about 0.55 m to a peak of 1.3 m. Following the peak, the stage gradually decreased to 0.8 m. It is very difficult to explain this phenomena on the basis of the meteorologic observations. Prior to this date the temperatures averaged well below 0°C although there were a few days when the maximum temperature climbed above +5°C. No significant precipitation was recorded at Whitecourt, Campsie, or Slave Lake and there was no melt at the Twin Lakes snow pillow. It may be possible that outflows from the Little Paddle River may have contributed to the stage fluctuations.

On March 16, a major increase in stage, lasting until March 24, began to take place. This stage increase occurred simultaneously with the one on the Little Paddle River. Observations on March 19 showed that the Paddle River was completely open upstream of the Little Paddle River confluence (figure 10) and downstream of the Little Paddle River confluence (figure 11). At the latter location there was evidence of

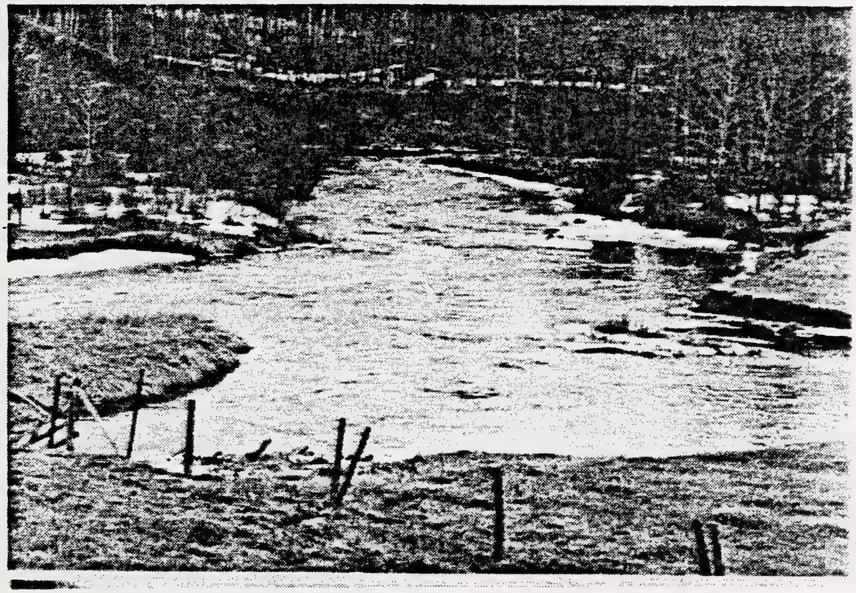

Figure 9. Open water on the Little Paddle River near Mayerthorpe, March 19, 1985

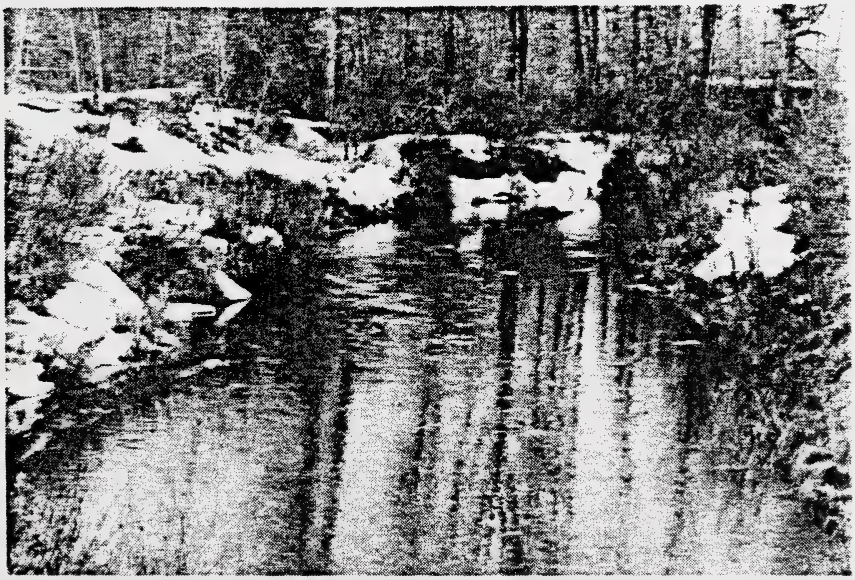

Figure 10. Open water on the Paddle River upstream of the confluence of the Little Paddle River, March 19, 1985

remnants of a light ice run with the previous stage being about 0.3 m higher. The flow on the Little Paddle River seemed to be augmenting considerably the Paddle River flow and the ice run probably resulted from the Little Paddle River. This open water extended downstream past Hwy 764 to somewhere upstream of the next bridge site where an intact ice cover was observed (figure 12). The cover was deteriorated considerably but had not been noticeably moved downstream. However, further observations at Wahl's Bridge (downstream of Mosside) indicated that the cover had been fractured and displaced (figure 13).

At Barrhead the ice cover had the appearance typical of a thermally deteriorating cover. Numerous open areas where evident (figure 14) but the ice was still in place in a majority of the reaches. Figure 15 illustrates the longitudinal cracking along the channel center line resulting from the raising of an ice cover that is frozen to the bed along the banks. The overflow along the banks indicates that the stage had recently exceeded the pre-breakup ice level. Upstream of the confluence with the Pembina River, the cover appeared to be relatively intact (figure 16). The stage increase evident at Barrhead was not so evident at the mouth. More surface melting than upstream was evident but the ice cover was relatively intact without numerous open areas.

Following the peak stage on March 21, the stage gradually declined as the air temperatures were reduced to near zero and sub-zero values. The minimum stage of 1.25 m occurred on March 30, and by March 31 the stage began to increase again to a peak of 2.15 m on April 2. This is most likely in response to the melt which had also affected the stages on the Little Paddle River. Observations on April 1 indicated that the majority of the ice was gone, except for the odd local accumulation (figure 17). One can only speculate whether the ice cover was removed during the recession from the March 21 peak or whether it was removed during the rise in a stage prior to the April 2 peak. Given the characteristics of the accumulations, the latter is the most likely case. Following a sharp 0.3 m drop in stage during the afternoon of April 2, the stage was relatively constant for about four days until it slowly began to recede.

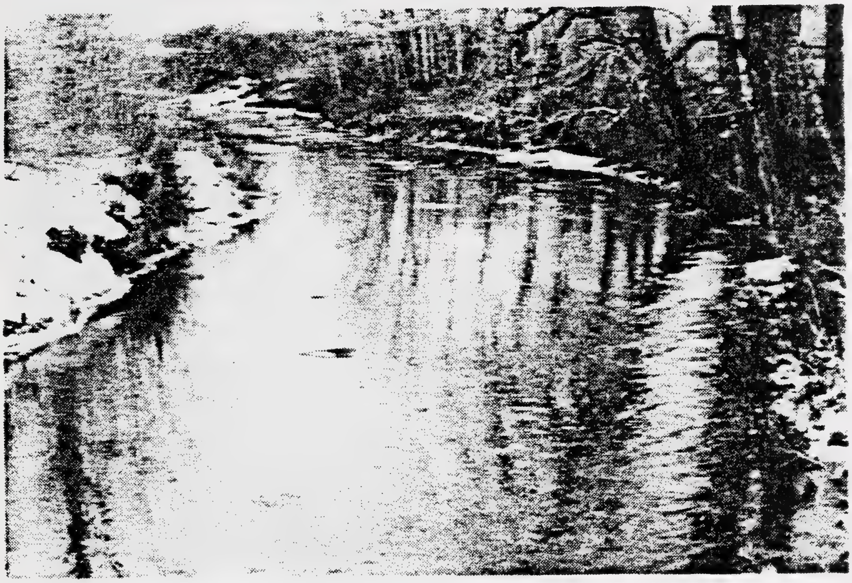

Figure 11. Open water on the Paddle River downstream of the confluence of the Little Paddle River, March 19, 1985

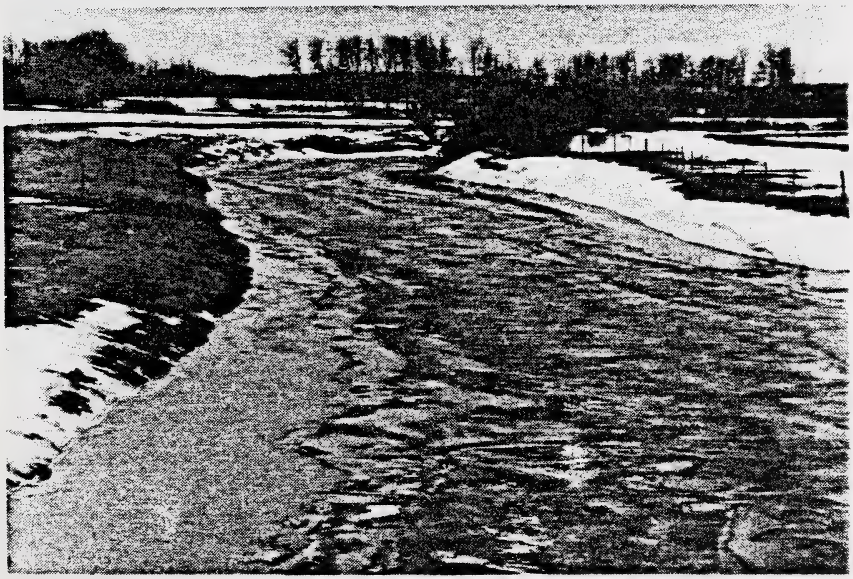

Figure 12. Intact ice cover on the Paddle River upstream of bridge crossing 6 km west of Mosside, March 19, 1985

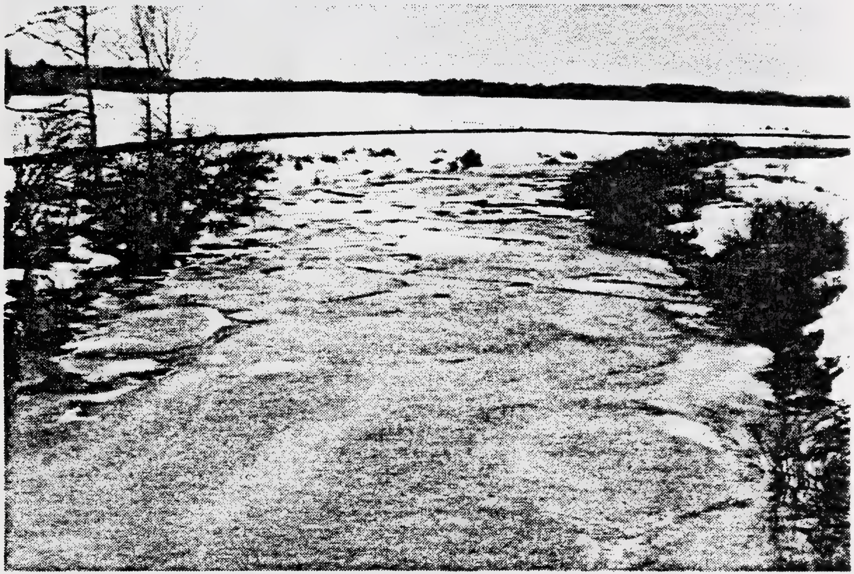

Figure 13. Fractured ice cover on the Paddle River upstream of bridge crossing 8 km west and 3 km south of Barrhead, March 19, 1985

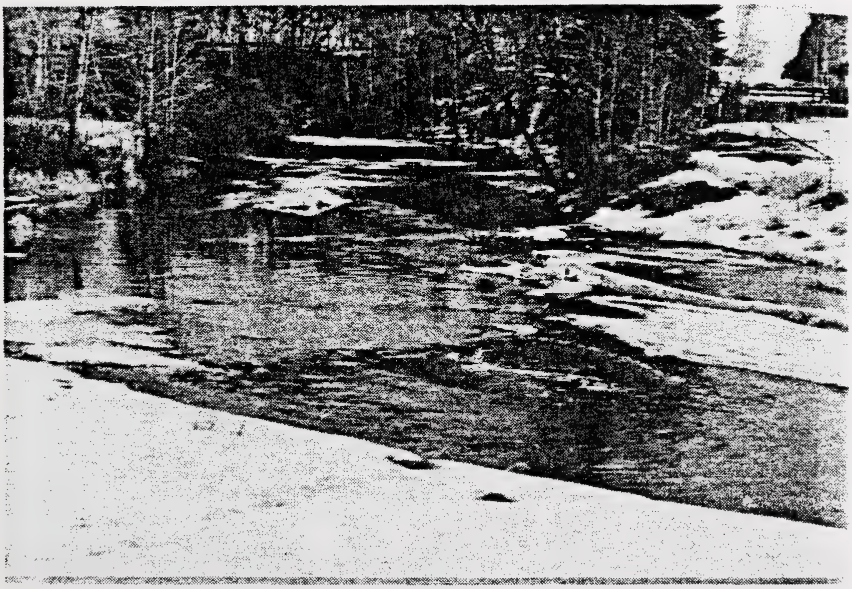

Figure 14. Fractured ice cover and overflow on Paddle River downstream of bridge crossing at Barrhead, March 19, 1985

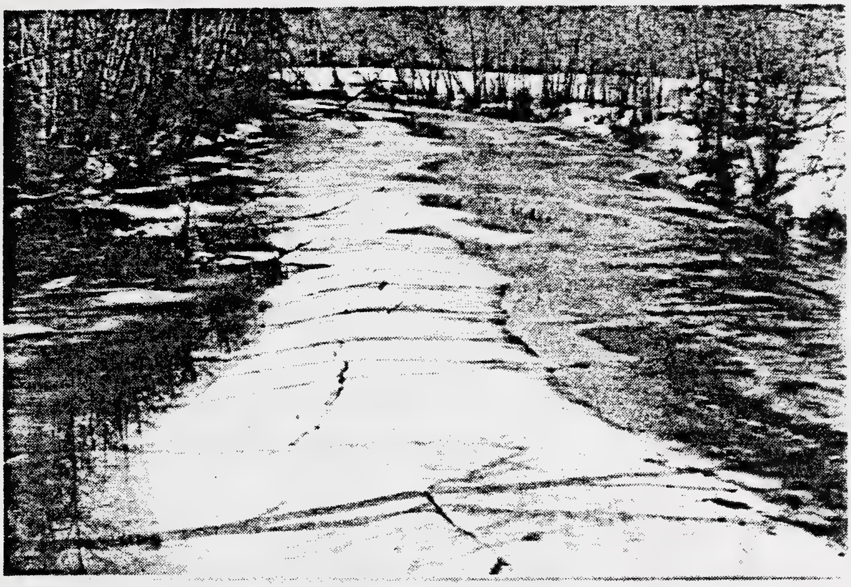

Figure 15. Fractured ice cover and overflow along the bank on the Paddle River upstream of the Barrhead bridge crossing, March 19, 1985

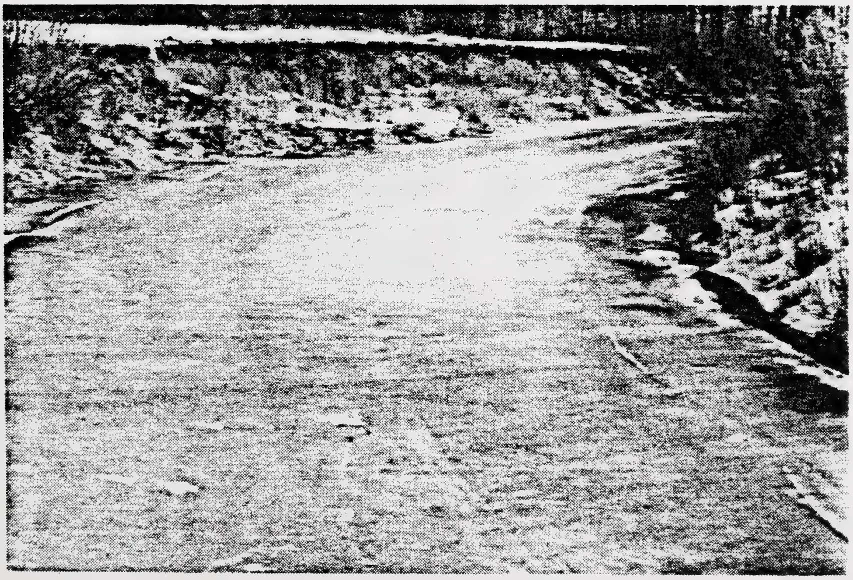

Figure 16. Intact ice cover on the Paddle River at the first bridge crossing upstream of the mouth, March 19, 1985

Pembina River

During the early part of March, the water level on the Pembina River remained relatively stable at a gauge height of 1.2 m at the WSC gauge at Jarvie. On March 19, however, the Pembina River exhibited a stage increase at about 0.8 m over a period of about four days. This was probably in response to the melt which produced stage increases on the Paddle River on March 16 and on the Little Paddle River sometime earlier. Observations on March 19 at Belvedere (figure 18) indicated that the ice was still snow covered with no signs of being disturbed but with melt water ponded in some areas.

The gauge at Jarvie held steady at about 2.0 m until March 31, when it slowly began to rise, reaching a peak of 3.65 m on April 5. This is concurrent with the stage increases on both the Little Paddle and Paddle Rivers. The gauge height remained in that vicinity for about three days, until April 7, and then rapidly receding to 2.0 m by April 10. On April 1, the Pembina River was observed to be ice bound upstream of the mouth of the Pembina river (figure 19). The open flow on the Paddle River had little impact on the Pembina River ice (figure 20). There was considerable melt along the edge with some open areas evident. These characteristics were maintained downstream past Rossington (figure 21) to Pibroch, where the open leads become more predominant (figure 22) and about 50 percent of the channel could be considered to be open. At Jarvie, in the vicinity of the WSC gauge, the ice cover was intact with fewer open areas. Downstream of Fawcett, where the channel slope steepens, the cover appeared to be considerably less competent and on the verge of disintegration even though long open leads were not visible (figure 23). Some short accumulations of ice were apparent at the downstream end of some of the open sections. Areas with considerable overflow were also evident.

On April 6, the last day of high stage at Jarvie, the ice cover still had not moved in the river reaches upstream of Fawcett. However, its destruction was nearly complete. At Manola (figure 24) the cover had been broken into large sheets of about one to two channel widths in

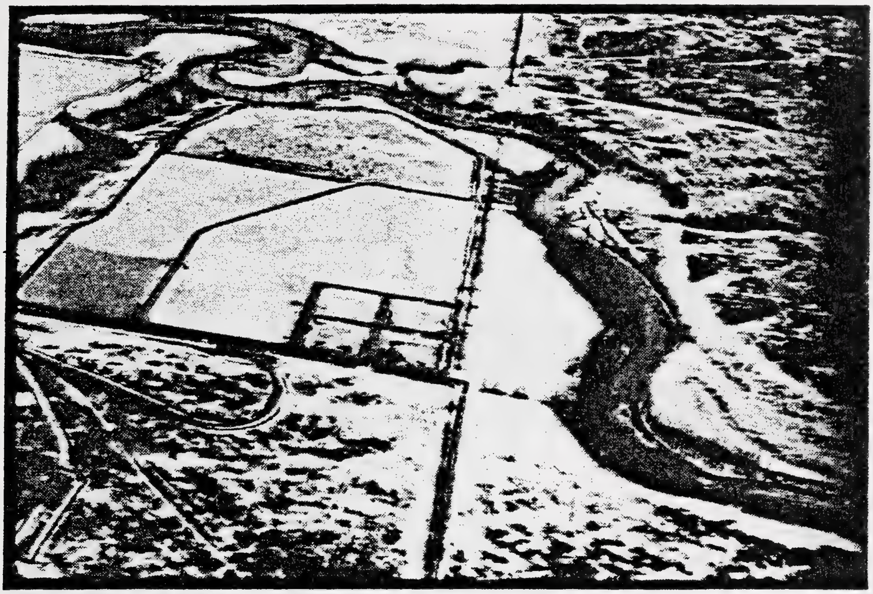

Figure 17. Open water and accumulated broken ice on the Paddle River near the sewage lagoons, downstream of Barrhead, April 11, 1985

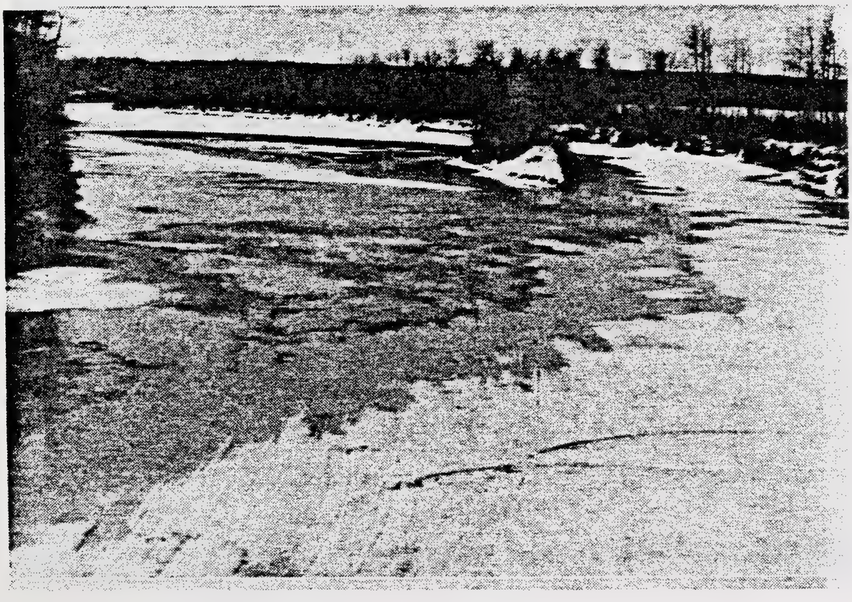

Figure 18. Flow over snow covered ice on the Pembina River upstream of the bridge crossing at Belevdere, March 19, 1985

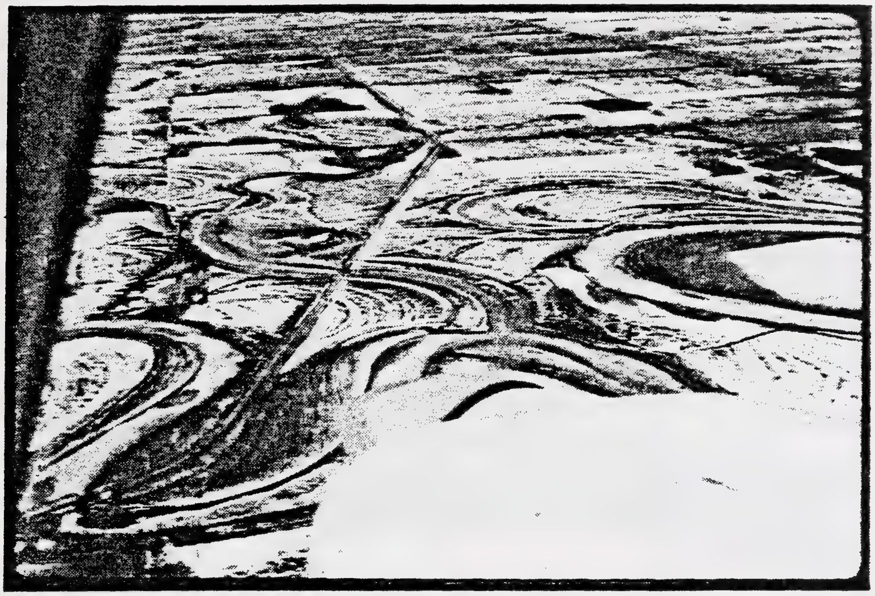

Figure 19. Ice cover on the Pembina River upstream of the mouth of the Paddle River, April 1, 1985

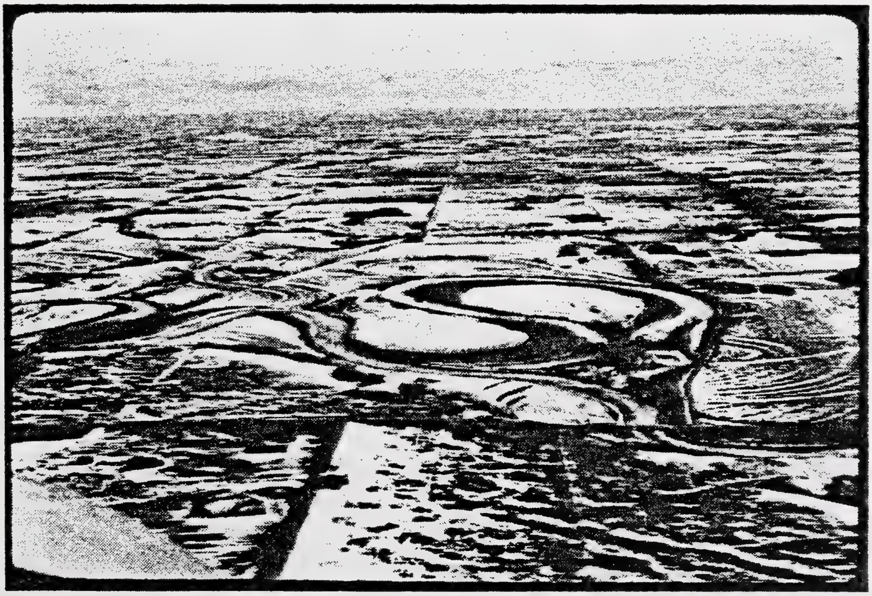

Figure 20. Ice cover on the Pembina River downstream of the mouth of the Paddle River, April 1, 1985

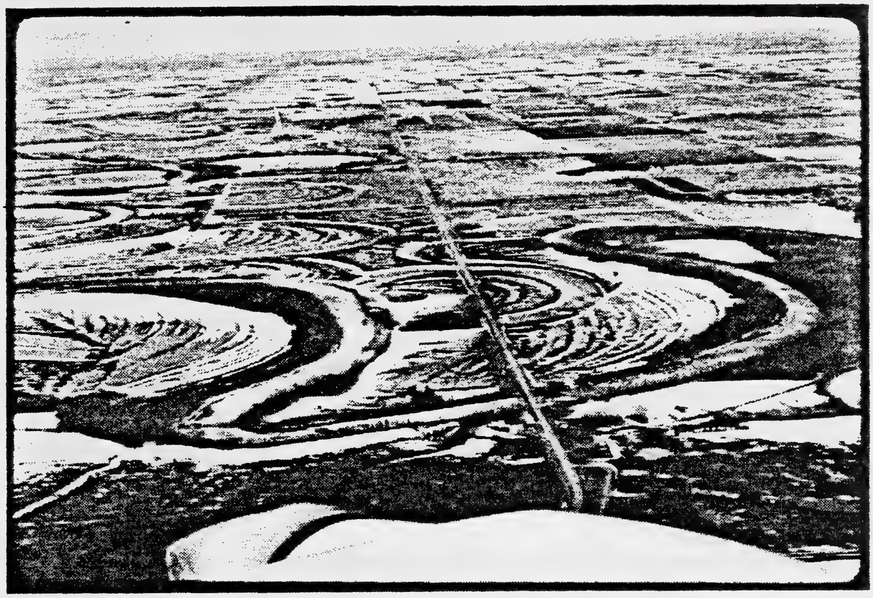

Figure 21. Ice cover on the Pembina River at Rossington, April 1, 1985

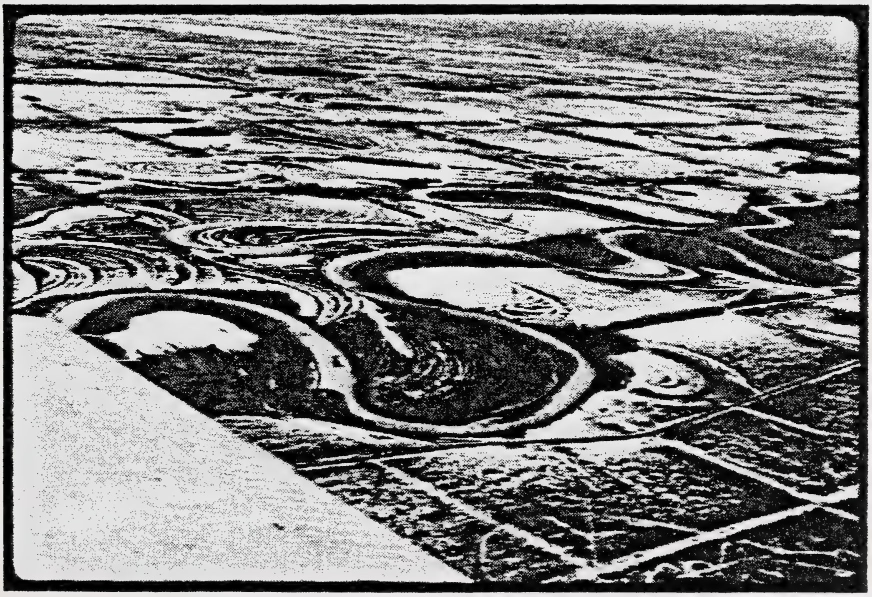

Figure 22. Ice cover with considerable open water on the Pembina River at Pibroch, April 1, 1985

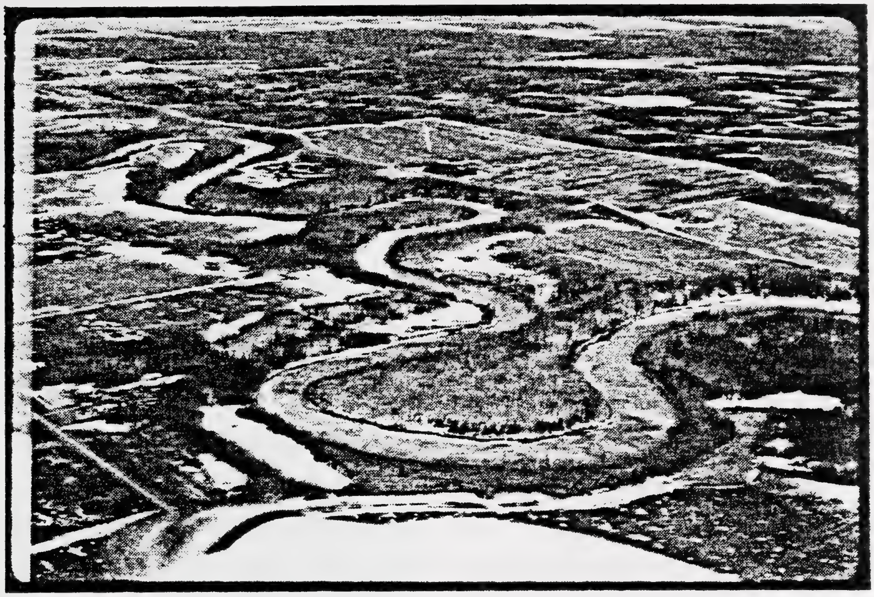

Figure 23. Ice cover on the Pembina River downstream of Fawcett, April 1, 1985

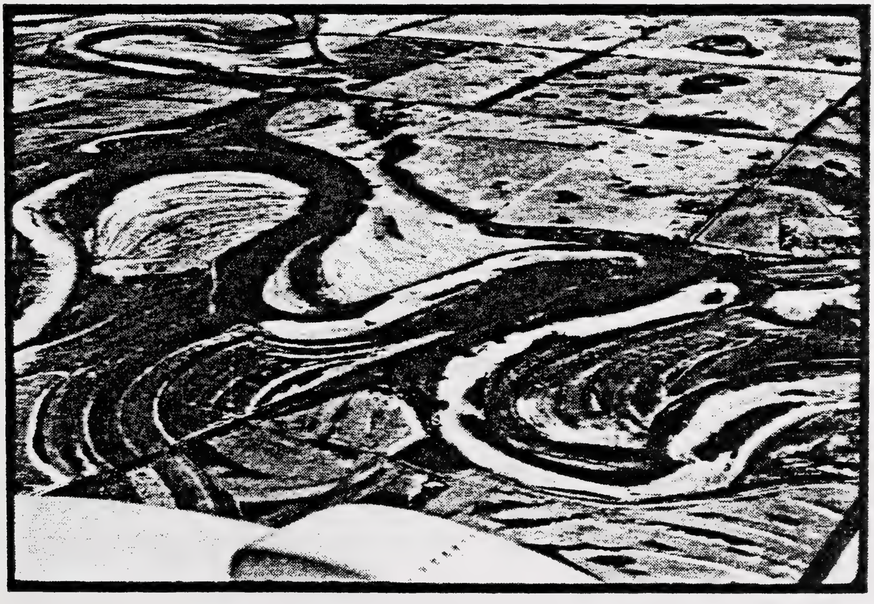

Figure 24. Intact, but nearly destroyed ice cover on the Pembina River upstream of the mouth of the Paddle River, April 1, 1985

length and many long reaches were completely ice free. The ice which still remained in the channel was not being moved downstream. The cover was still intact at Rossington (figure 25). In the vicinity of Pibroch much of the river was open (figure 26), but at Jarvie the cover was intact at the gauge (figure 27). This intact cover appeared to be a local phenomenon because downstream at the mouth of French Creek the cover was obviously broken, although there was limited downstream shoving (figure 28).

Downstream of Fawcett, the river was completely open from bank to bank (figures 29) and a ten kilometre long jam was located at the confluence with the Athabasca River (figure 30). This jam had pushed out a distance of only about one river width into the Athabasca River. It appears that about 60 km of river ice from as far upstream of Fawcett, had moved downstream and consolidated into a 10 km long jam. This would suggest that the thickness of the accumulation was in the order of three times the average pre-breakup ice thickness if it assumed that 50 percent of the ice had been melted prior to the run.

The WSC gauge observer at Jarvie indicated that a downstream movement of the ice cover was first observed on April 9. From the evidence on the WSC chart (figure 8) this probably occurred at about 22:00 hours on April 8. This was about two days after the stage began to recede and indicates that the breakup at Jarvie was over-mature. A stage increase to 3.60 m was insufficient to produce breakup without considerably more melting. This melting was only achieved on April 18, at which time the breakup occurred independently of the discharge.

Athabasca River

Observations on the Athabasca River were carried out periodically between April 4 and April 18. These observations were conducted mostly by aircraft although there was a period of time when only limited ground reconnaissance could be made. The record of the breakup sequence illustrated in figure 31 is the result of the observations.

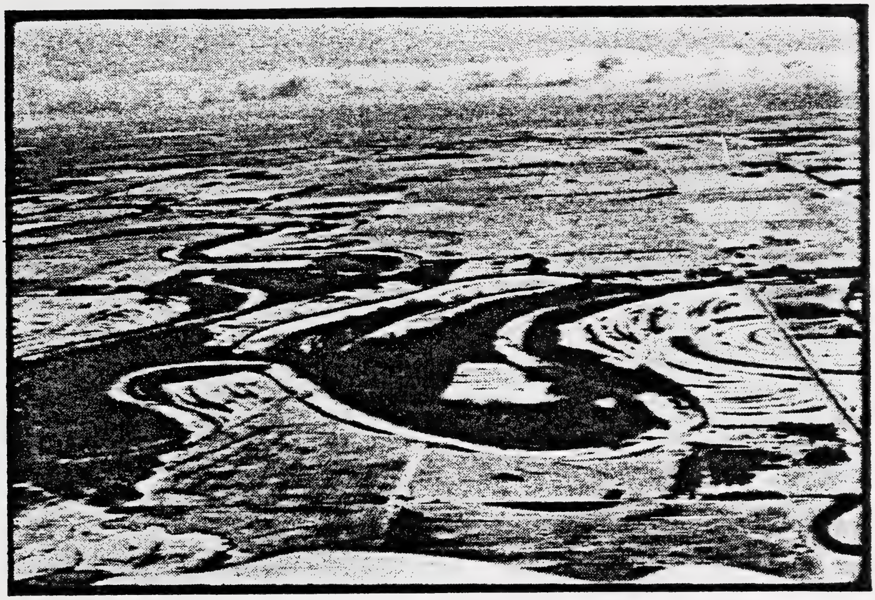

Figure 25. Intact ice cover with minimal leads on the Pembina River at Rossington, April 6, 1985

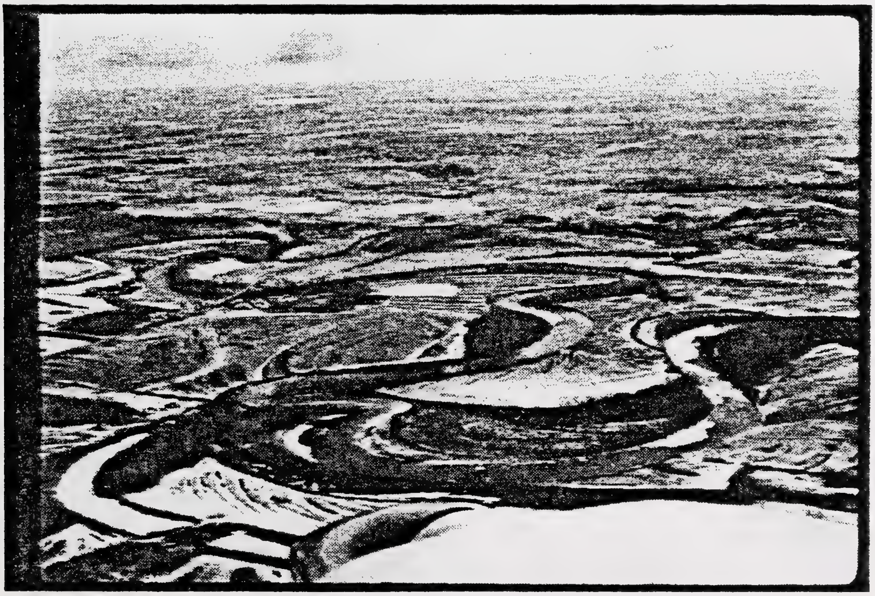

Figure 26. Intact, but nearly totally destroyed (thermally) ice cover on the Pembina River at Pibroch, April 6, 1985

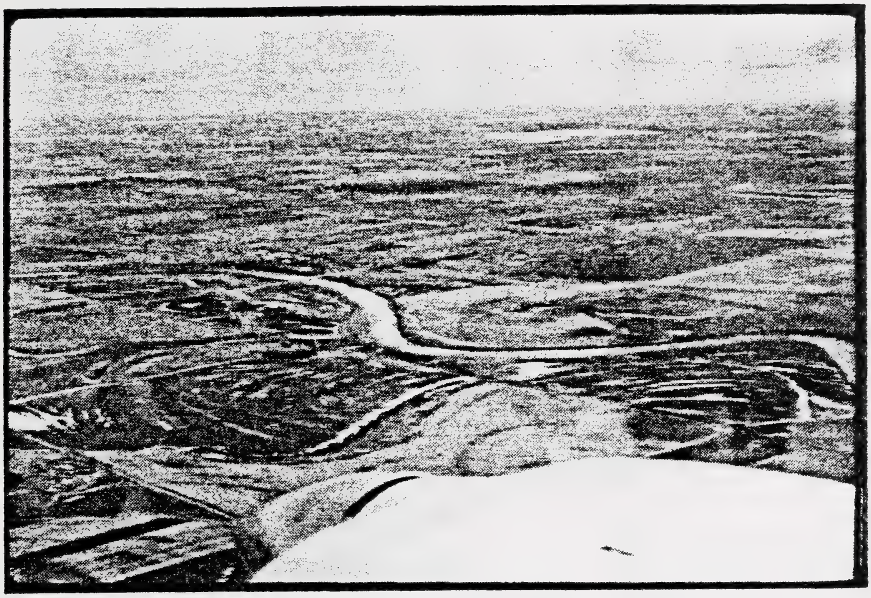

Figure 27. Intact ice cover on the Pembina River at Jarvie, April 6, 1985

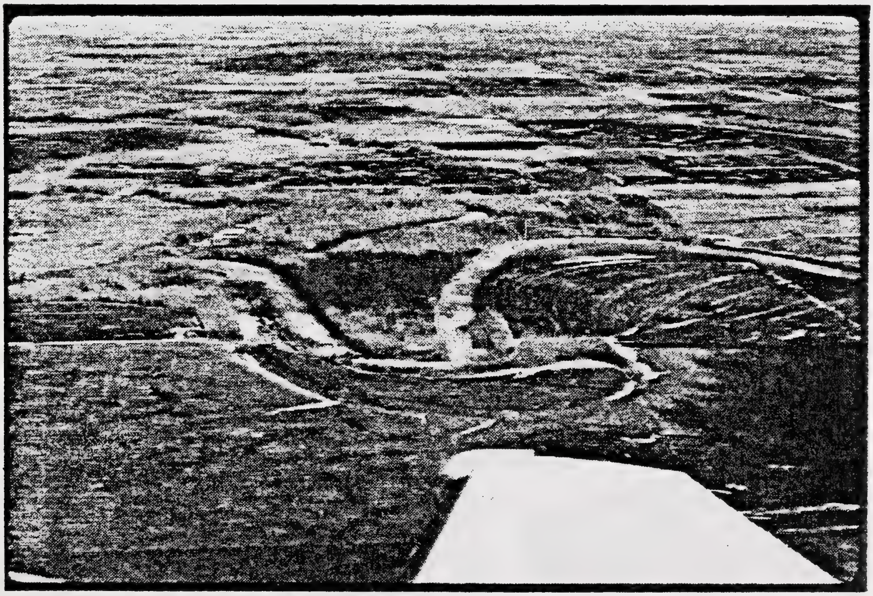

Figure 28. Fractured and transported ice on the Pembina River at the mouth of French Creek, April 6, 1985

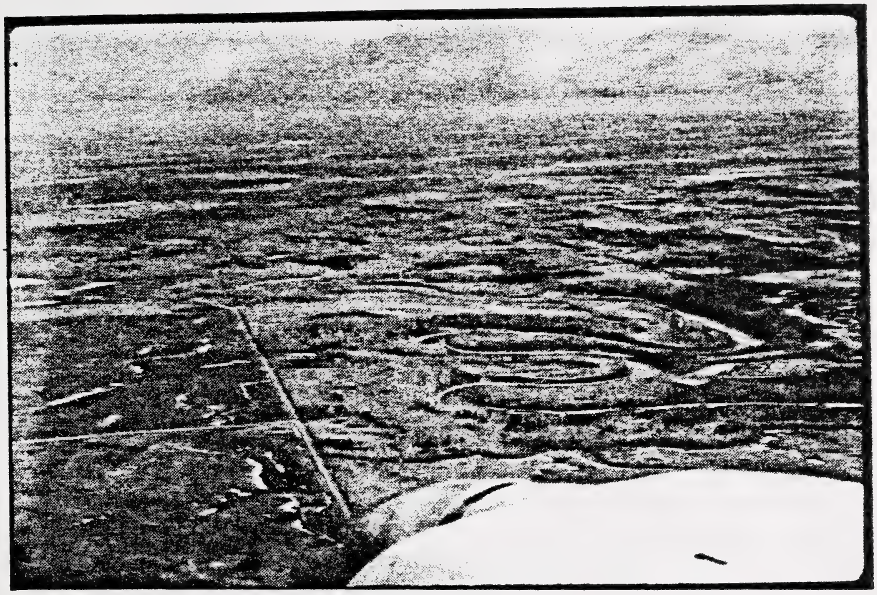

Figure 29. Open water on the Pembina River downstream of Fawcett, April 6, 1985

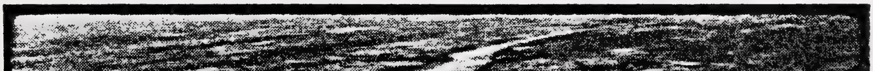

Figure 30. The toe of a 10 km long jam on the Pembina River at its confluence with the Athabasca River April 6, 1985

Figure 31. The progression of breakup between the mouth at the Pembina River and Suncor on the Athabasca River, April 1985

On April 1, a limited aerial reconnaissance indicated that there was no activity on the Athabasca River between the mouth of the Pembina River and Smith. Downstream of Smith, the Athabasca River also showed no signs of impending breakup. The majority of the cover was still white, except where thermal ice formed in previously open leads. There was no border melt and the cover showed no signs of being lifted or moved. The Tawatinaw River and Muskeg Creek had spilled ice into the Athabasca River, but without a major impact. The ice at the Town of Athabasca looked very solid with a whitish appearance. Downstream of Athabasca, the ice cover looked extremely strong although somewhat more mottled than upstream. This may have been due to a reduced accumulation of snow. There were no open leads visible until near the mouth of La Petit Riviere Jaillante, downstream of which open leads were observed around the island located north west of Corrigall Lake, at the mouth of Duncan Creek, and at Iron Point. Downstream of Iron Point the river was generally solid, until numerous open leads (1/10-1/20th of the channel width) were evident through Pelican Rapids and through Rapides du Joli Fou.

At the mouth of the House River, there was some open water resulting from the pipeline installation but from there, downstream to Grande Rapids the cover was intact with no open leads. From the open section at the rapids, open leads (approximately 1/5 of the channel width) extended downstream for about 5 km, at which point the cover was solid for as far downstream as Brule Rapids, where open leads were once again evident. Downstream of there, open water was evident at most of the rapid sections, especially at Boiler Rapids, with intact ice found between the rapids. Significant open leads were also observed at Long Rapids, Mountain Rapids, and Little Cacade Rapids. Both Cascade Rapids, and Mountain Rapids showed numerous small open leads or overflow across the whole width of the channel.

On April 6, there were only minor changes to the ice conditions. Upstream of the mouth of the Pembina River, the cover was virtually intact with no signs of melting. The ice run on the lower Pembina River created a long lead along the right bank of the Athabasca River, down-

stream of the confluence. It also appears that the increase in discharge associated with the ice run on the Pembina River caused the ice on the Athabasca River to be lifted, fractured laterally from bank to bank, and moved to a small degree downstream. These fractures (figure 32) occurred at spacings of about 10 channel widths and persisted downstream only as far as Chisholm.

Downstream of Chisholm, the ice cover was intact except for the odd leads. Most notable were the characteristic open areas at Rourke Creek (upstream of Hwy 2) and in the vicinity of the island located downstream of Hwy 2. The Lesser Slave River had not yet cleared itself at its mouth. In the reach between Smith and Athabasca, the river was ice covered with the odd open lead evident. These open leads were particularly apparent in the straight reach of river south west of Calling Lake where the channel slope seems to be somewhat steeper. Both Muskeg Creek and the Tawatinaw River had gone out and created some open water along the right bank of the Athabasca River through the Town of Athabasca (figure 33). Downstream of the Town of Athabasca the cover was intact and not noticeably deteriorated. Open leads were evident in numerous locations, particularly in the vicinity of Iron Point, Pelican Rapids, Grande Rapids, and the various other rapid sections between Brule Point and Mountain Rapids.

On April 9, the ice between Rourke Creek and the Hwy 2 bridge crossing dislodged itself and moved downstream past the highway bridge. This may have been triggered by the clearing of the ice cover between the mouth of the Pembina River and Hondo Creek which resulted in a jam (first observed on April 10) at the mouth of Hondo Creek. On April 11, this jam was still lodged in at Hondo Creek. The head could not be observed although the length of the jam was somewhere between 4 and 10 km long, because open water was evident as far downstream as was visible from Chisholm. Access made it difficult to estimate the height of the jam. At Chisholm there was evidence of a very small ice run (approximately 1 to 1.5 m above present water level). The height of the shear walls along the left bank (as photographed from right bank) were approximately 2 m.

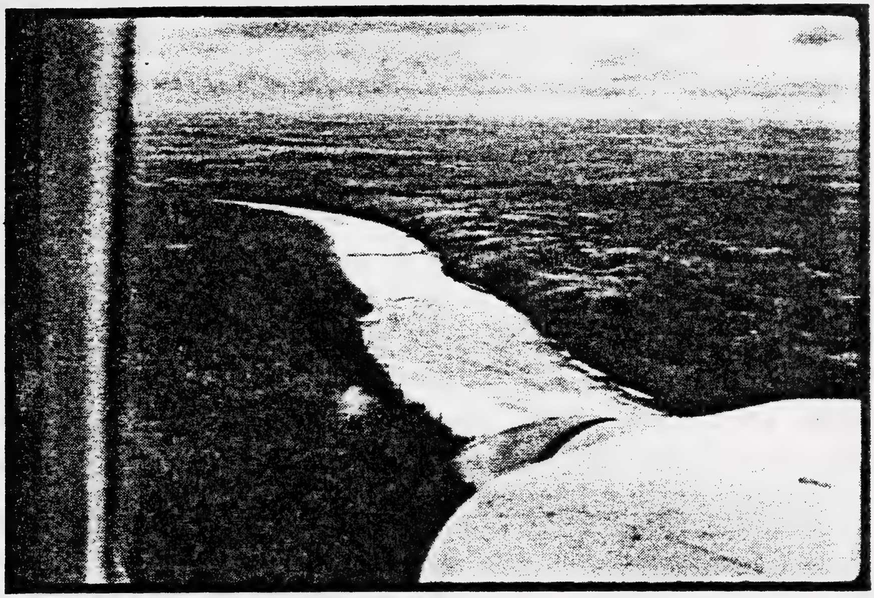

Figure 32. Lateral fracturing of the ice cover on the Athabasca River downstream of the mouth of the Pembina River, April 6, 1985

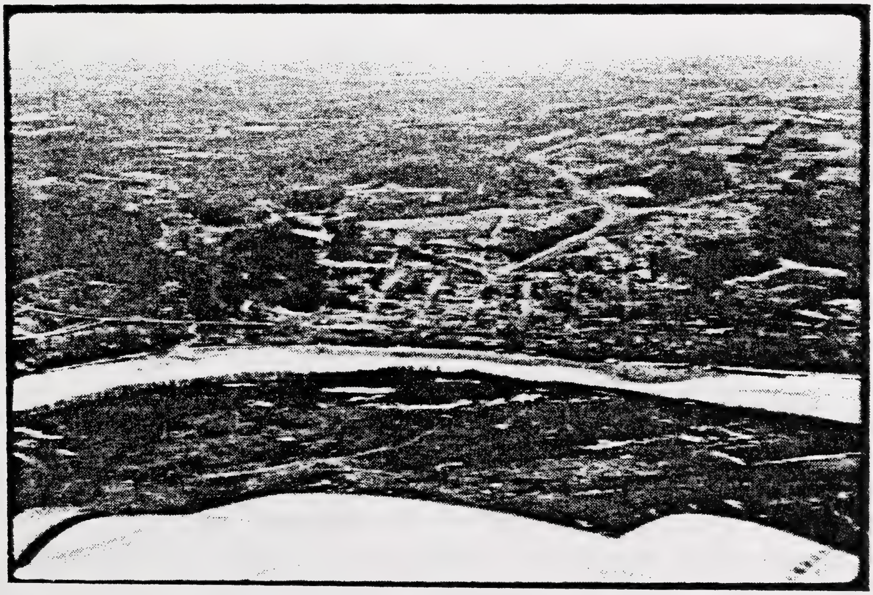

Figure 33. Leads developing along the right bank of the Athabasca River at the Town of Athabasca, April 6, 1985

Additional observations on April 11 indicated ice movement at the Town of Athabasca. This appeared to result due to a gradual increase in stage of 0.8 m at the WSC gauge between April 10 and April 11 (figure 34). The gauge observer indicated that first movement occurred at a gauge height of 2.8 m at 0:600 hours of April 11. The disturbed ice cover was confined to a very short reach and created open water conditions for three to four channel widths downstream of the highway bridge at Athabasca, and for a distance of about five channel widths through the town. Most of the broken floes were not overturned, submerged, or crushed to any great extent (figure 35). Apparently the cover rearranged itself and filled in the areas which were previously open. Upstream of the town, the cover was intact but its surface had a mottled appearance and seemed to be fractured transversely at the odd location. No predominant downstream movement could be observed.

No observations of the ice cover could be made between the Town of Athabasca and Smith. At Smith, however, there was localized open water about one to two kilometres upstream and downstream of the bridge but no sign of an ice run. It appears that the cover melted in place or simply moved downstream (figure 36) into previously unidentified open water.

The Hondo Creek jam, observed earlier, broke late on April 11. The ice and water surge reached the Hwy 2 bridge at 0:00 hours on April 12 and ran for about one hour. By 06:00 hours the river was jammed from downstream of the island below the bridge to as far upstream as the mouth of Hondo Creek. This jam produced a stage increase of 2 m at the bridge. At about 11:00 hours on that same day, the jam released and the head moved downstream to the Hwy. 2 bridge (figure 37). By 16:00 hours, a further consolidation moved the head to the upstream point of the island located downstream of the bridge.

An aerial reconnaissance on April 13 established that the Athabasca River ice was intact upstream of the Pembina River, but about 30 percent of the channel was open. There was insufficient discharge to move the existing ice downstream so it was rotting in place. Downstream of the Pembina River, open water without flowing ice was evident as far

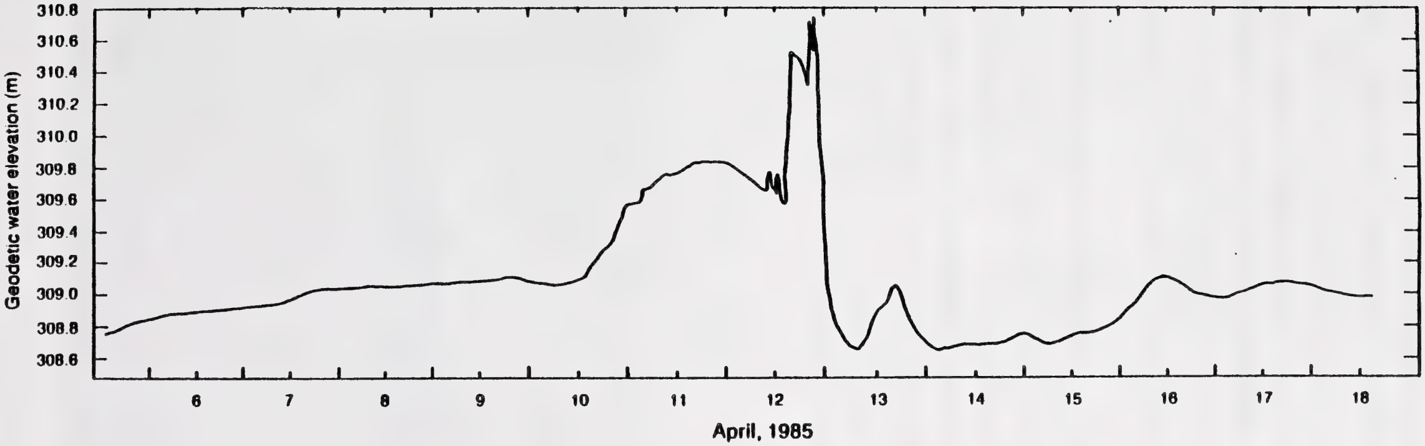

Figure 34. Water levels during breakup on the Athabasca River at WSC Gauge #07BE001, April 1985

as the Hondo Creek jam which was still positioned between Smith and Hwy 2 and had a length of 9 km. This jam appeared to have intercepted all the ice from upstream, because downstream there was mostly open water punctuated by short sections of intact ice, some very deteriorated ice, some running ice, and a 5 km long jam with its toe positioned at km 742, some 56 km upstream of the Town of Athabasca. Downstream of that jam, which isolated all the ice upstream, there was a long stretch of open water, leading up to a 64 km length of running ice.

This ice run, whose leading edge was located just west of Corrigall Lake at km 592, had passed the WSC gauge at the Town of Athabasca at 18:00 hours on April 12 (figure 34). If it is assumed that the run was continuous between Athabasca and its present location, its celerity would be about 1.6 m/s. At Athabasca, the rise in stage was about 1 m from the pre-run ice level. Once the run moved past the town, the stage dropped 2 m, to a stage of 1.8 m. The duration of the run at Athabasca

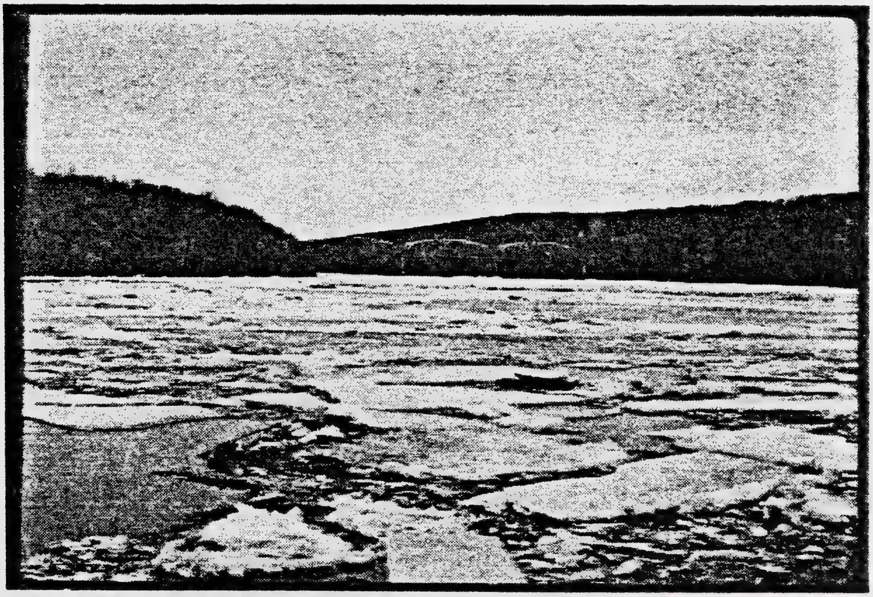

Figure 35. Fractured and transported ice cover on the Athabasca River at the Town of Athabasca, April 11, 1985

was about 12 hours, which would suggest a length of about 70 km, assuming an average celerity of 1.6 m/s. This coincides fairly well with the observed length of 66 km.

Downstream of the running ice, there was open water, but with evidence of a previous run. This open water extended downstream for 15 km to Duncan Creek where the head of another jam was located. This jam extended 13 km downstream to its toe, located just west of McMillan Lake. Downstream from this point the ice cover was intact, but with approximately 50 percent of it having melted out. There were numerous open leads such as at Iron Point (figure 38) but no apparent downstream movement of the cover. This condition prevailed as far downstream as the 20th baseline (a distance of 20 km) until open water was again observed. There were signs of a low ice run for the next 22 km, leading

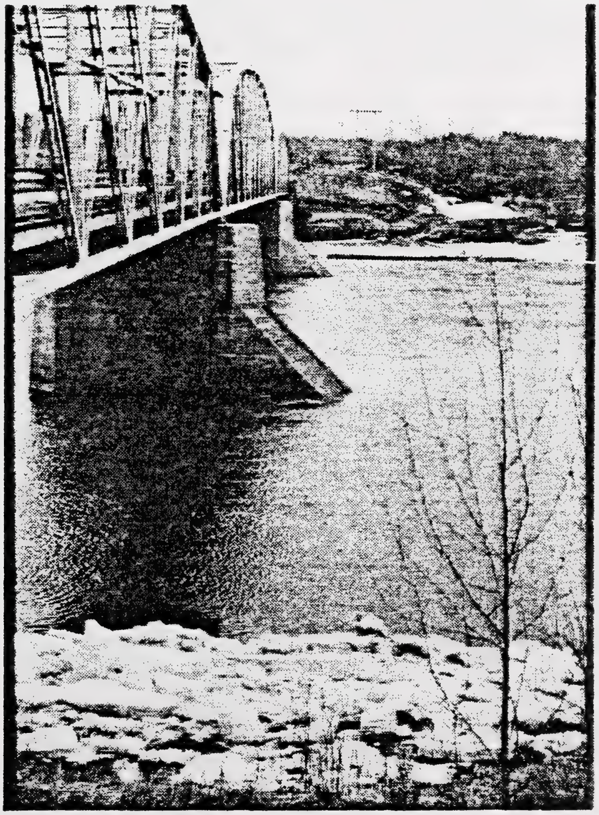

Figure 36. Open water and evidence of only a minor stage increase associated with the removal of the ice cover on the Athabasca River at Smith, April 11, 1985

up to a 8 km long jam with its head at the mouth of Parallel Creek. The toe of this jam was impinging against a solid cover (figures 39 and 40) which was generally intact, although more open leads were evident since the last observation on April 6. This intact ice cover extended downstream past the House River, where approximately 70 percent of the channel was ice covered, to Grande Rapids, below which approximately 7 km of open water had developed. Downstream of the stretch of open water, the channel was ice covered except for localized open areas, some open leads through the rapid sections, and what appeared to be some large sheets recently broken up in the vicinity of Point La Biche (immediately downstream of the open water below Grande Rapids). The open leads through the rapids were somewhat larger than observed on April 6, however, it did not appear that significant enlargement had occurred. Downstream of the mouth of the Alger River, there was a stretch of open water leading up to a short 3 km long jam impinging against an intact ice cover at Long Rapids. This cover exhibited numerous open leads in

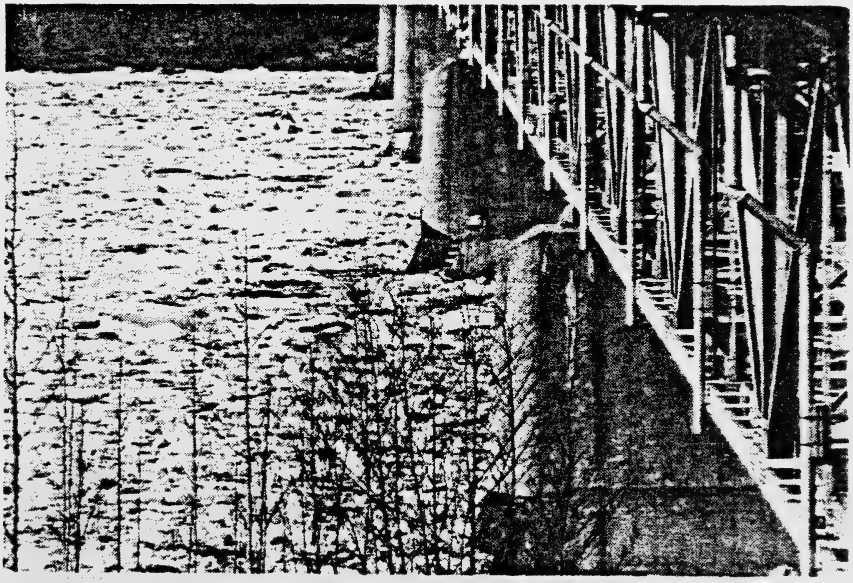

Figure 37. Peak stage at the Hwy 2 bridge crossing of the Athabasca River at Hondo, following the formation of an ice jam downstream, 15:00 hours, April 12, 1985

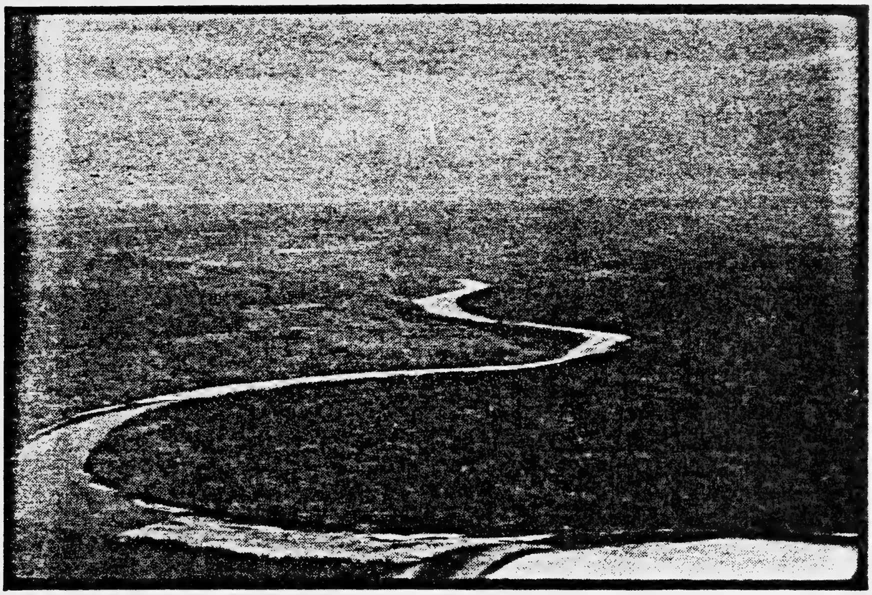

Figure 38. Intact but deteriorating ice cover on the Athabasca River near Iron Point, April 13, 1985

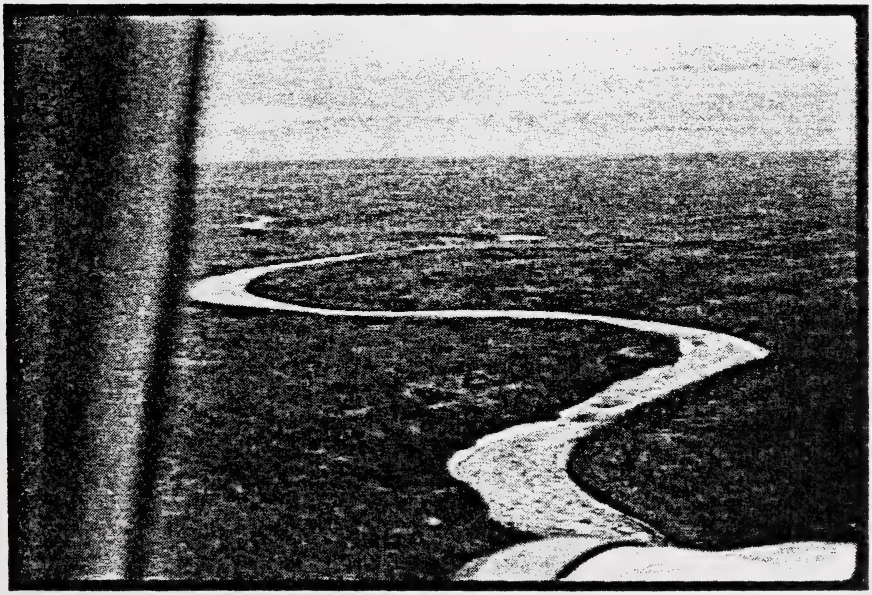

Figure 39. Intact and competent ice cover on the Athabasca River downstream of Stony Rapids, April 13, 1985

the section between Long Rapids (figure 41) and Little Cascade Rapids. However, downstream of the latter location, the cover was virtually intact (figure 42) except for some significant open leads at Mountain Rapids.

At the experimental ice movement station, installed downstream of Rock Rapids to remotely warn of impending breakup by transmitting ice movement data to GEOS (Rachuk and Rickert, 1985), minor ice movements were detected on April 11 at 13:00 hours and at 23:00 hours. On April 12, an additional downstream movement in the ice cover was detected at 16:22 hours and a major change in the ice cover was again apparent on April 13 at 14:50 hours. Unfortunately no observations could be made to identify the configuration of the ice cover but the station identified a downstream shift of at least 100 m or one quarter of the channel width.

By April 14, the assortment of ice observed on the previous day, in the reach between Hondo and km 740, had moved downstream. The WSC gauge records at Athabasca indicate a small run passed the gauge between 13:00 hours on April 13 and 0:600 hours on April 14. This same run was observed on April 14 with its leading edge near the mouth of the La Biche River. This suggests a celerity of 0.70 m/s. The duration of the run at Athabasca was 17 hours, suggesting a length of 43 km. This is more than twice the observed length. It is possible that there may have been a flood wave behind the ice run which added to the duration of the stage increase associated with the run of ice at Athabasca.

The running ice observed downstream of Athabasca on April 13 had, by this time, moved through the intact ice cover at Iron Point and was running into a 9 km long jam keyed against an intact ice cover at Stony Rapids (figure 43). This intact cover extended downstream to Rapides du Joli Fou, below which open water was encountered. This open water extended to downstream of Brule Rapids where the head of the running ice was located. The ice run was moving through relatively deteriorated ice and the toe of the run was observed at Cascade Rapids at 10:33 hours (figure 44), probably having moved past the ice station within the half

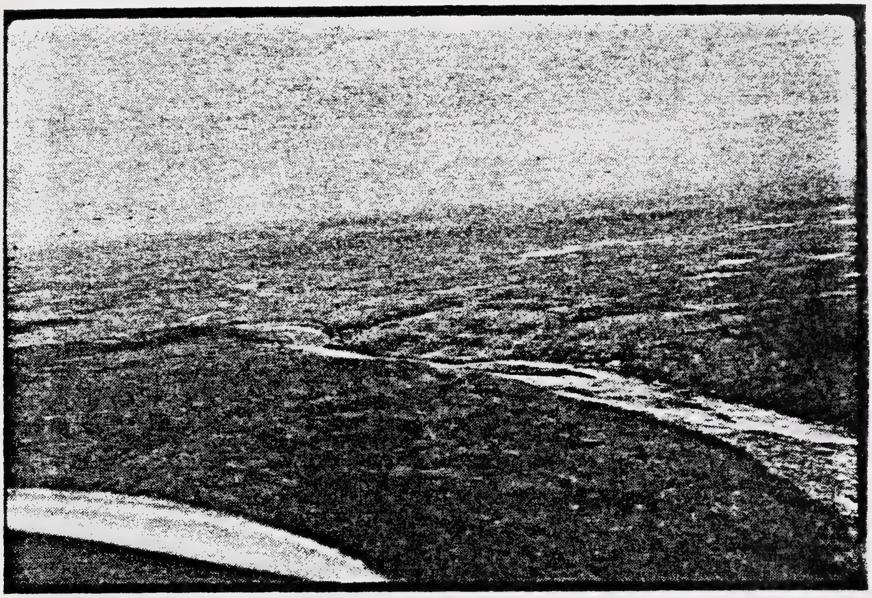

Figure 40. Competent ice cover on the Athabasca River upstream of Grande Rapids, below which the channel is completely open, April 13, 1985

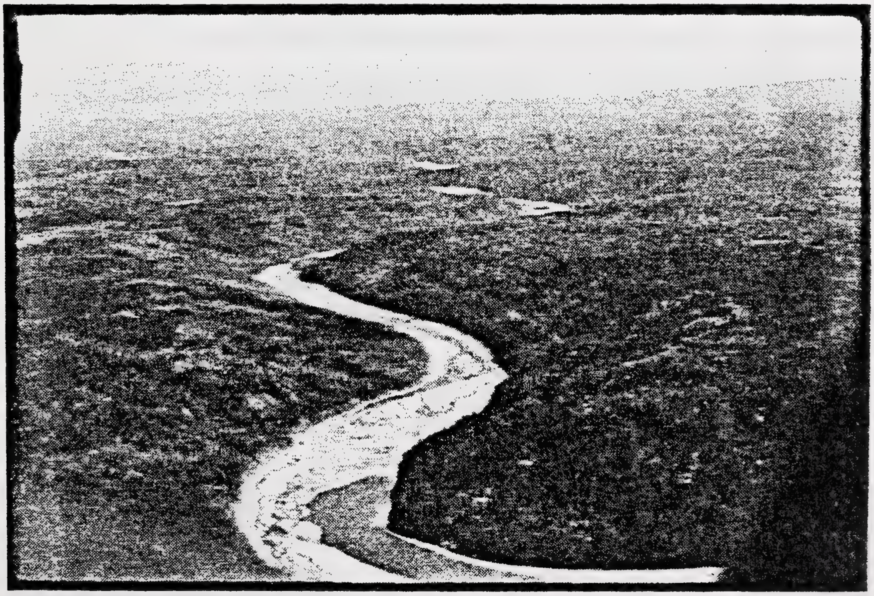

Figure 41. Deteriorating cover with numerous leads and open areas on the Athabasca River at Long Rapids, April 13, 1985

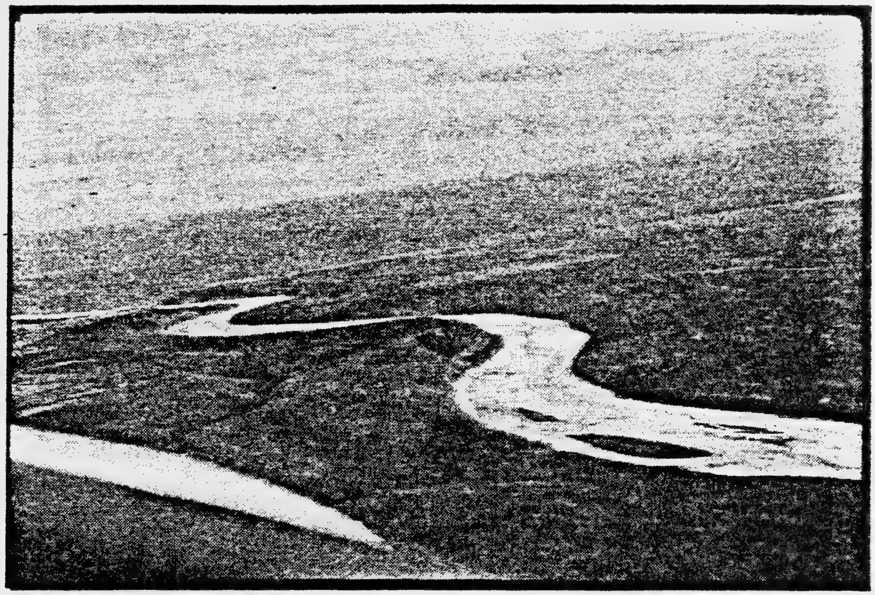

Figure 42. Virtually intact ice cover on the Athabasca River downstream of Mountain Rapids, April 13, 1985

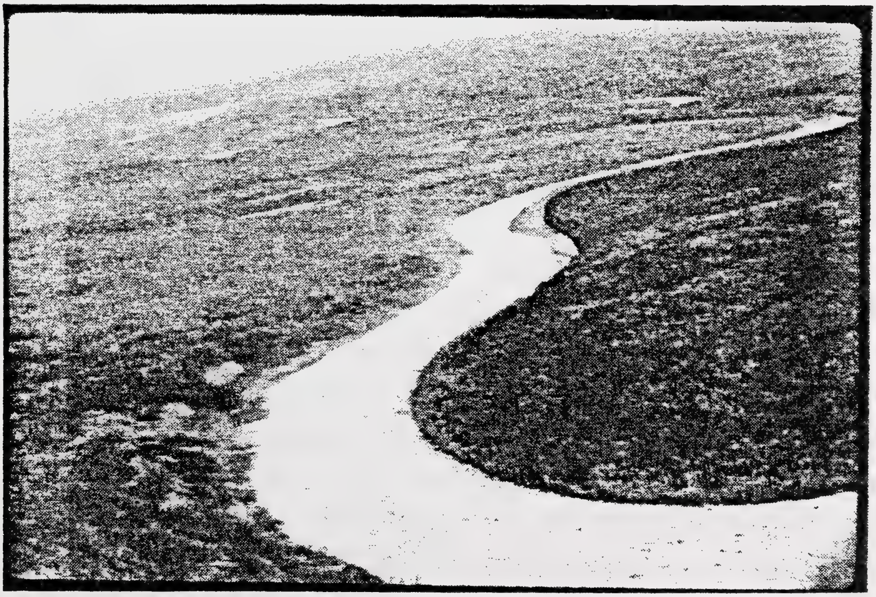

Figure 43. Toe of an ice jam keyed into competent ice on the Athabasca River at Stony Rapids, April 13, 1985

hour. Apparently the ice in the reach upstream of Grande Rapids went out during the morning of April 14. At the mouth of the House River, observers indicate that the ice went out suddenly at 02:00 hours with a stage increase of about 4 m. This would indicate that the ice front moved downstream at a celerity of 3.9 m/s, between the House River and Cascade Rapids.

At approximately 11:20 hours, on April 14, the moving ice stopped just upstream of Mountain Rapids at km 314 (this results in a celerity of 3.5 m/s) and an extremely stable jam formed. It is interesting that from approximately 145 km of river, only an 18 km long jam was produced. This jam remained in place at least until April 18 at 20:00 hours when it was last observed. During this time the ice downstream of Mountain Rapids continued to deteriorate (figure 45). At 18:30 hours on April 18, the solid ice cover upstream of the MacEwan Bridge began to break up. Between 19:00 and 20:00 hours a helicopter reconnaissance was made but due to darkness the breakup process could not be observed in its entirety. The ice downstream of Mountain Rapids produced a small run past the MacEwan Bridge, leaving ice stranded along the banks (figure 46). No jamming was observed during this run. An instantaneous stage increase of 2.0 m above the pre-breakup water level to a maximum water level of 244.5 m was observed (although the observers indicate a somewhat lower peak as shown in figure 47) at 22:00 hours. Similar increases were also recorded on the Clearwater River, which was still ice covered, but this modest increase in stage was of limited concern.

During the events leading up to the formation of the jam upstream of Mountain Rapids, the WSC gauge downstream of Fort McMurray revealed little about what was occurring upstream (figure 48). Between April 12 and April 14 the gauge showed diurnal fluctuations of about 0.1 to 0.2 m. On April 14, a sudden and dramatic rise occurred at 14:00 hours, just 2.5 hours after the jam formed upstream. This suggests that the water wave accompanying the moving ice continued downstream without breaking the ice cover downstream, even after the ice was arrested. The timing of the various events suggests a water wave celerity of about 2.2 m/s. Unfortunately the gauge malfunctioned at 15:00 hours on

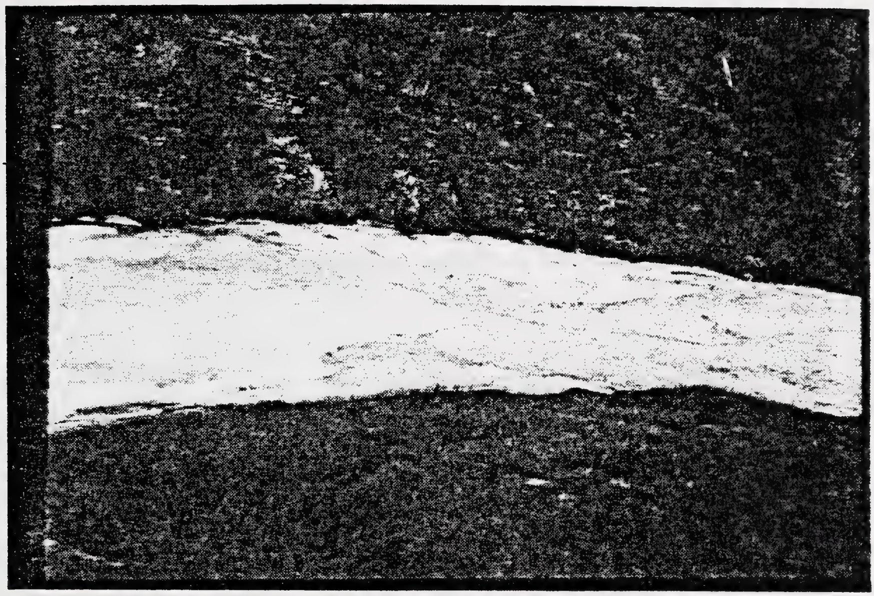

Figure 44. Toe of running ice on the Athabasca River downstream of Cascade Rapids, 10:25 hours, April 14, 1985

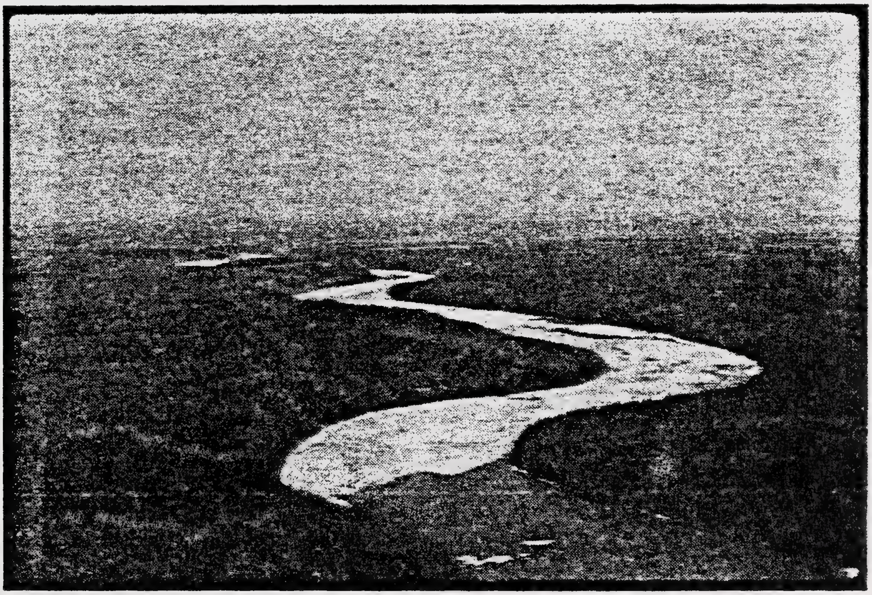

Figure 45. Rapidly deteriorating ice cover on the Athabasca River downstream of Mountain Rapids, April 15, 1985

April 14 and was not operational until 20:20 hours on April 19, well after the ice run from downstream of Mountain Rapids passed the gauge.

A brief reconnaissance on April 17 indicated that the ice cover was still intact in the sharp bend 6 km upstream of Rapides du Joli Fou (figure 49). This deteriorating cover extended upstream for 8 km until the toe of a 5 km long jam was observed. Upstream of the head, there was open water for about 3 km until the toe of another jam was observed. The toe of this jam was located about 4 km downstream of Stony Rapids, impinged on a solid ice cover, and extended upstream for 11 km to near the mouth of the Pelican River. There was no incoming ice from upstream. This jam is probably the same one observed on April 14. Since that date, the toe appeared to move 2 km downstream and the head moved 2 km upstream. This 4 km increase in the length of the jam was the result of the accumulation of the running ice observed downstream of Athabasca and between Iron Point and the head of the jam.

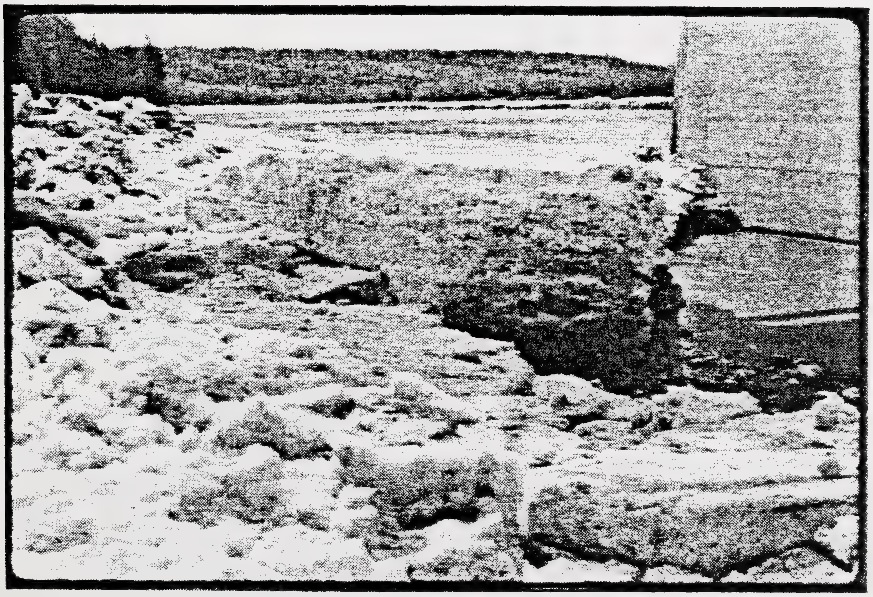

Figure 46. Remnants of the ice run of the Athabasca River at the MacEwan Bridge, April 19, 1985

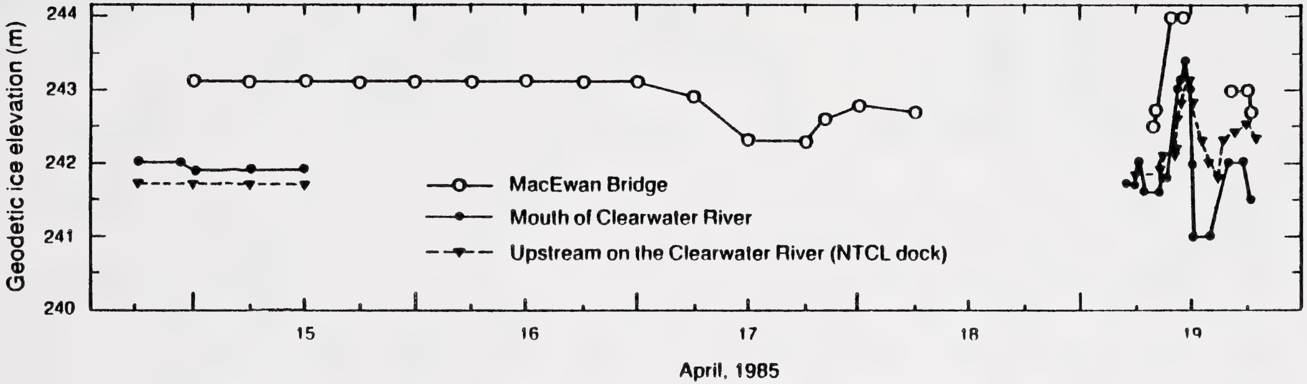

Figure 47. Water levels on the Athabasca River during breakup at the MacEwan Bridge, April 1985

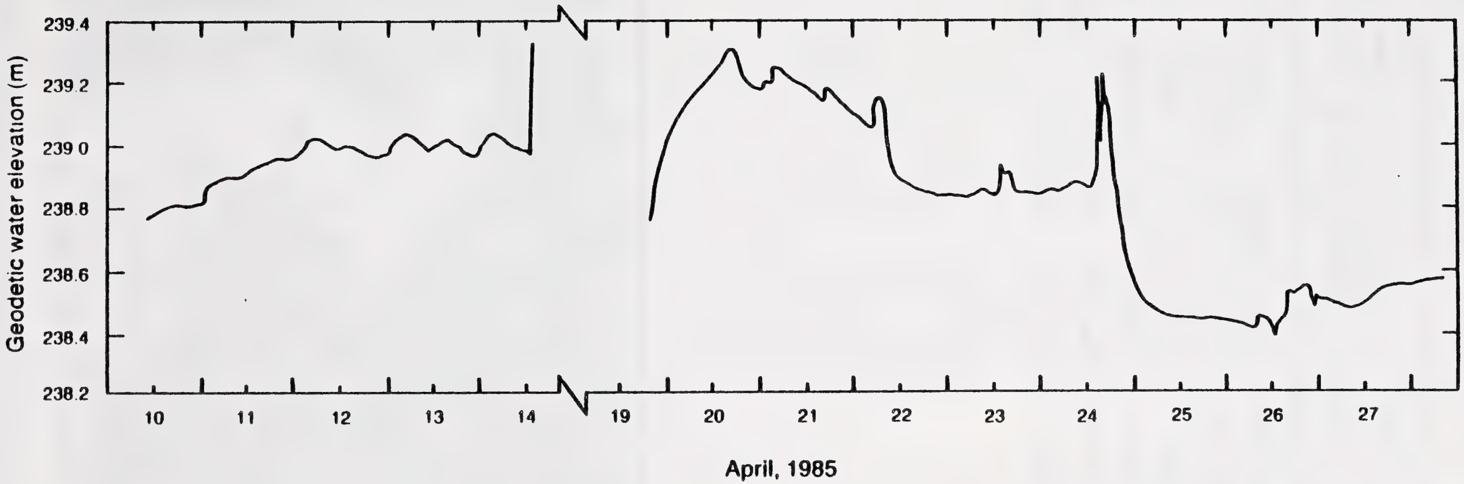

Figure 48. Water levels during breakup on the Athabasca River at WSC Gauge #07DA001, April 1985

It becomes apparent that approximately 380 km of ice was effectively segregated from the lower 160 km of ice and could not aggravate the jam which formed upstream of Mountain Rapids. This was extremely positive from a flooding point of view because, had more ice and water been available it may have been possible for the breakup front to move past Fort McMurray and produce a large jam at the mouth of the Clearwater River. In fact, with the stalling of the ice front upstream of Mountain Rapids, there was only 10 km of river ice available to form a jam downstream of Fort McMurray. This volume in itself would have been insufficient to produce significantly high water level at the mouth of the Clearwater River even if a jam had formed downstream.

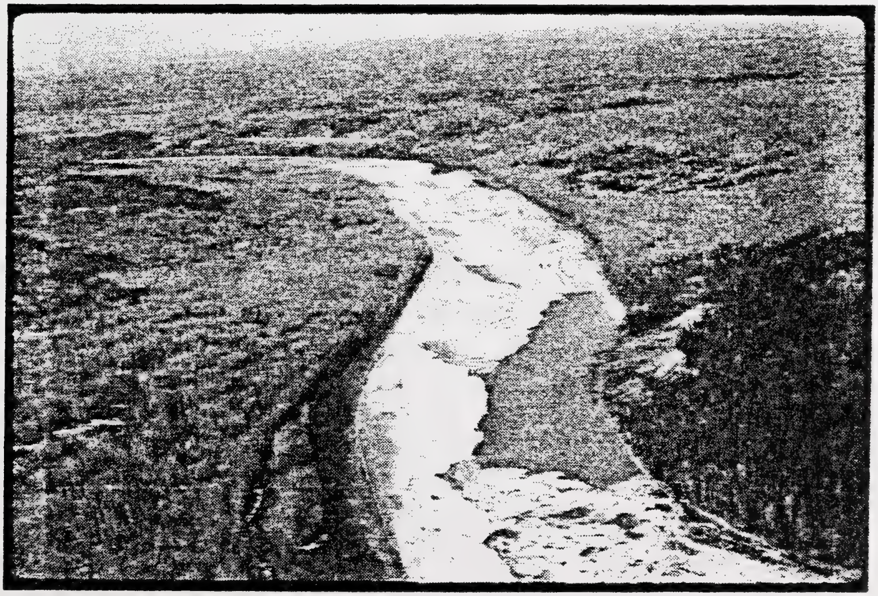

Figure 49. Intact but deteriorating ice cover on the Athabasca River downstream of Stony Rapids, April 17, 1985

ICE JAM DOCUMENTATION

Numerous jams were observed during the 1985 breakup. The most notable ones were on the Pembina River at its mouth and on the Athabasca River at Hondo Creek, at Hwy. 2, at Rapides du Joli Fou, and upstream of Mountain Rapids. Except for the jam upstream of Mountain Rapids, all the other jams either were difficult to access or the discharge at which they formed could not be readily estimated. As a result, only the jam upstream of Mountain Rapids was documented for the purposes of evaluating the roughness of its underside and its coefficient of internal friction.

The measurement of the jam, could only be done photographically from a helicopter due to poor accessibility by ground. During the formation of the jam, the position of the toe, the position of the head, and the various characteristics of the ice cover along the jam were recorded. Once the jam had stabilized, time was allotted to allow the discharge to drop sufficiently such that two profiles could be measured: the peak ice level and a somewhat lower ice level for some lower steady discharge. The ice jam levels were determined from oblique photographs at appropriate locations. Later in the summer, survey crews referenced the ice jam levels to identifiable features along the banks. These features were then referenced to both or either the water level on the day of survey and geodetic elevation. These points on the ice jam profile are thought to be accurate to within 0.5 m.

In the following sections, the physical characteristics of the jam such as length and height will be described. The channel characteristics will also be discussed and the discharge during the formation of the jam will be evaluated. As well, the hydraulic characteristics of the jam will be detailed along with aspects of its internal stability.

Physical Characteristics

Figure 50 illustrates the aerial extent of the documented ice jam.

Figure 50. Extent of the jam upstream of Mountain Rapids, April 14-16, 1985

The toe of the jam (figure 51) was located at km 313.5, about 5 km upstream of Mountain Rapids. It is apparent from the rearrangement of the bed (figures 52 and 53) that much of the toe had grounded out in what appears to be a very shallow river reach. The slope of the jam (figure 54) within the toe area (km 313.5 to km 314.2) was about 0.0034.

The equilibrium section of the jam (between km 314.2 and km 322.0) had a slope of 0.00076, similar to the open water slope if the very steep reach through Cascade Rapids is ignored. Figure 55 illustrates the arrangement of the floes within this reach. It is apparent that the thickness of the jam was greater than twice the thickness of the floes and that the cover was considerably consolidated. Within Cascade Rapids, an open lead had developed immediately after the formation of the jam (figure 56) and remained there for the duration of the observations.

Immediately after formation, the head of the jam was located upstream of Little Cascade Rapids at km 327. The ice cover at this location was extremely porous and approximately the thickness of one floe (figure 57). On April 15, after about 20 hours, the head of the cover had moved downstream a distance of about 0.8 km and by 12:00 hours on April 16 the head had moved another 1.2 km through Little Cascade Rapids to km 325. Upstream of the head, 4 m thick shear walls (figure 58) were left exposed following the passage of the ice run. This would suggest that the thickness of the jam should be at least in excess of 4 m.

The river reach within which the jam formed was characterized by eight surveyed cross sections. Some sections were referenced to geodetic elevation if geodetic bench marks were available. Other sections were referenced to an assumed datum. A reasonable profile could be established because a sufficient number of sections were surveyed to the same datum. The location of the surveyed cross sections is shown in figure 50 and the sections are illustrated in figure 59. At a discharge of 820 m/s the channel has an average top width of 460 m^3 and the flow has an average mean depth of 1.45 m (table 5). At this low discharge, the channel bed exhibits a Manning's roughness coefficient of 0.025.

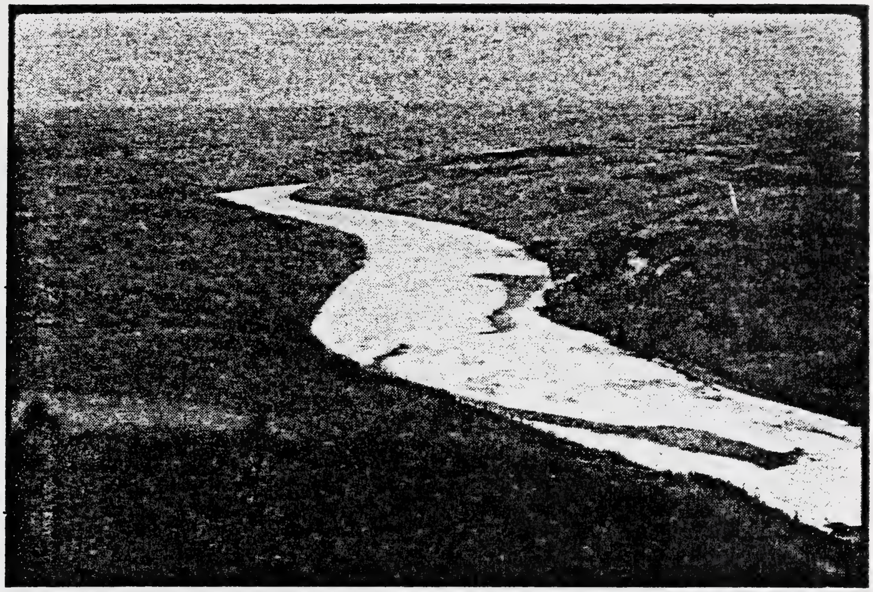

Figure 51. Toe of the documented jam upstream of Mountain Rapids April 15, 1985

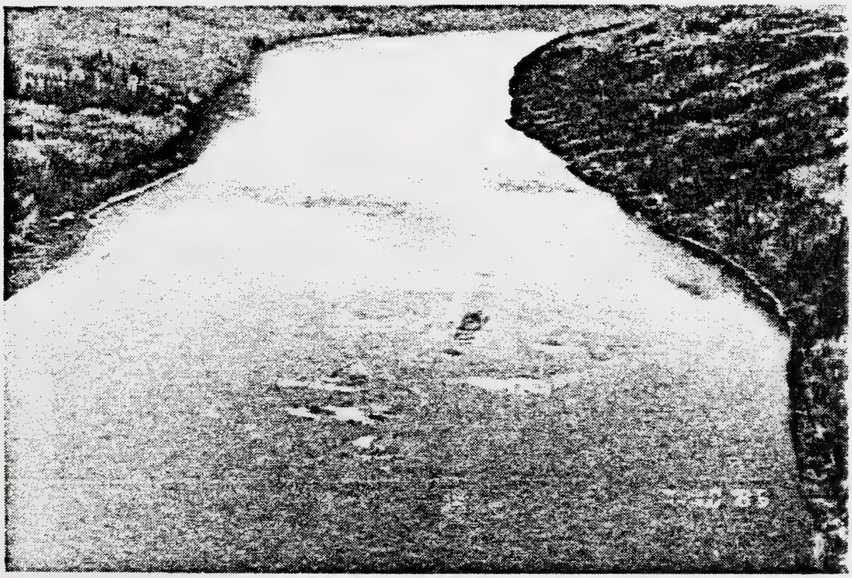

Figure 52. Rearrangement of the channel bed at the toe of the jam

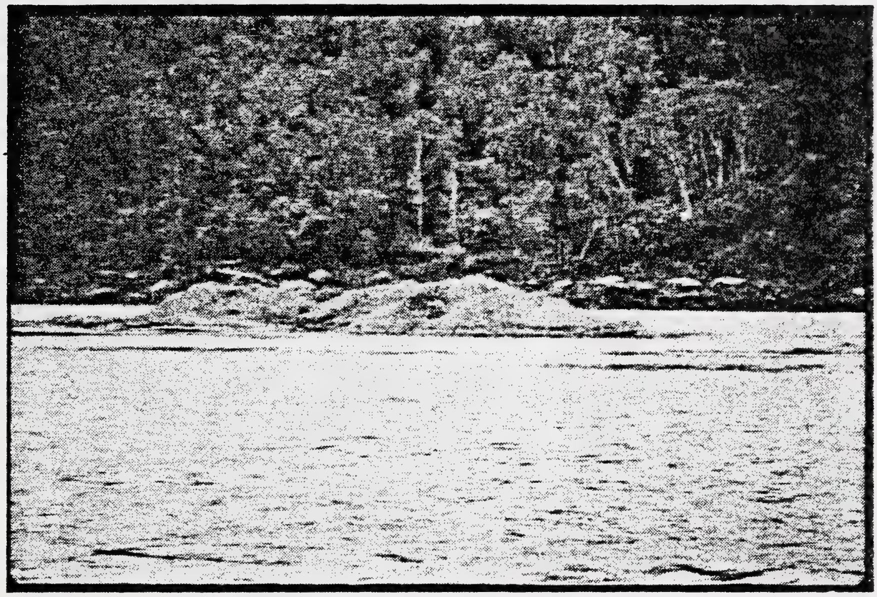

Figure 53. Disturbed bed material resulting from grounding at the toe of the jam

Table 5.

Summary of the Open Water Hydraulic Characteristics, $Q = 820\ m^3/s$

Cross Section (km)	Channel Slope (km/m)	Top Width (m)	Mean Depth (m)	Manning's Roughness
312.25	0.76	390	1.95	0.040
315.68	0.76	450	1.44	0.028
317.20	0.76	380	1.29	0.020
320.25	0.76	470	1.34	0.026
322.49	1.5[a]	410	2.20	0.072
324.20	0.76	500	0.89	0.014
327.30	0.76	450	1.40	0.026
328.65	0.76	610	1.05	0.022
Mean	-	460	1.45	0.031 0.025[b]

[a] non-uniform flow, slope may over estimated.

[b] excluding cross section 322.49

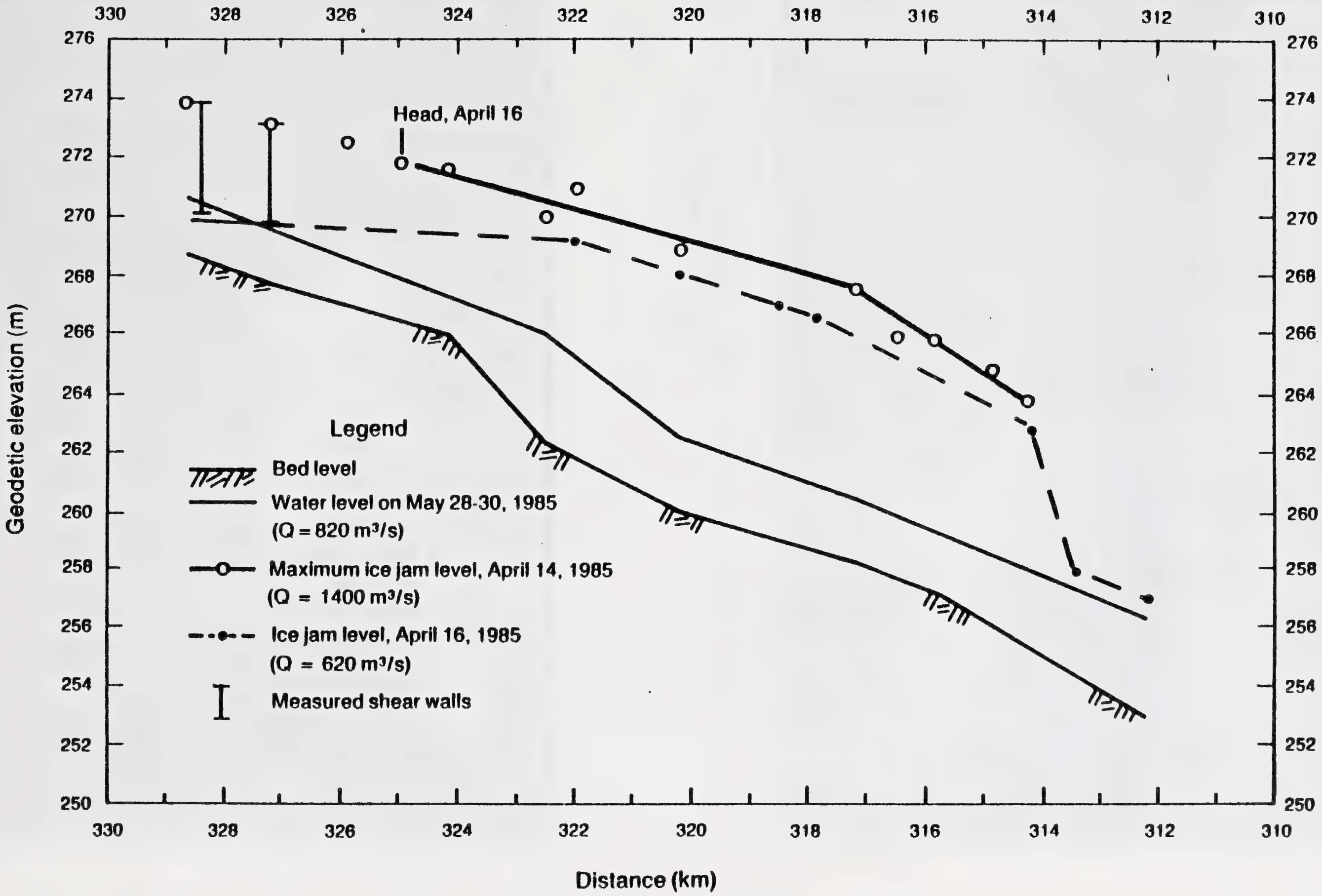

Figure 54. Ice level profile through the jam upstream of Mountain Rapids

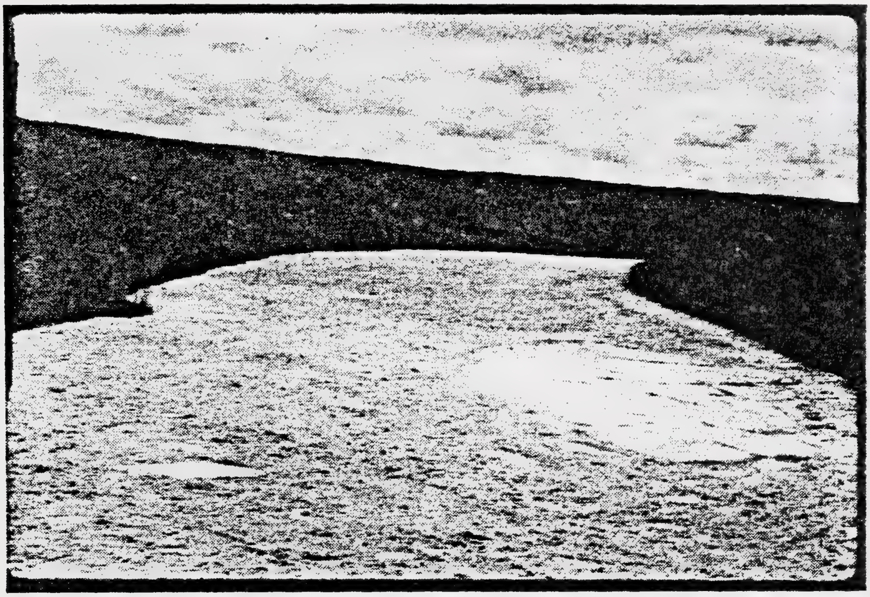

Figure 55. Floe orientation within the equilibrium reach of the documented ice jam

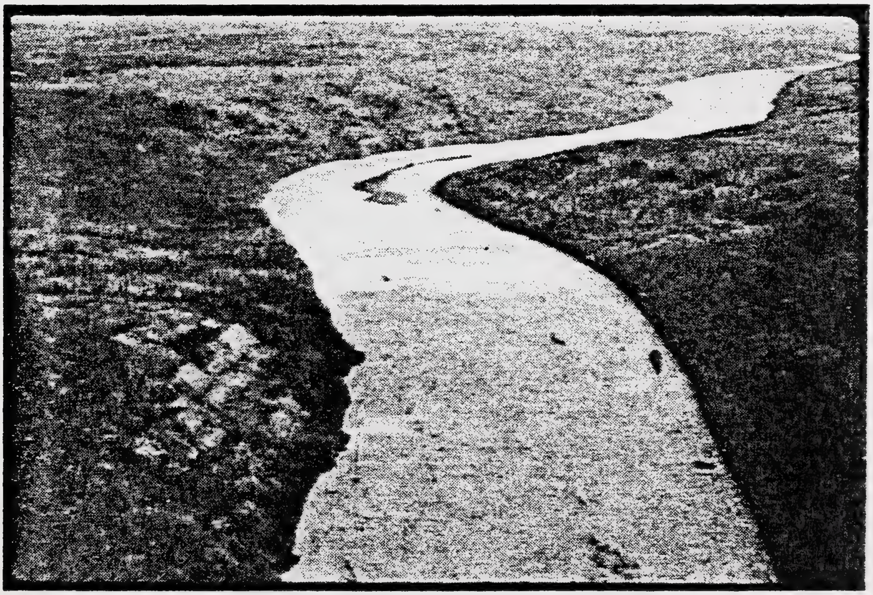

Figure 56. Open lead through the body of the ice jam at Cascade Rapids

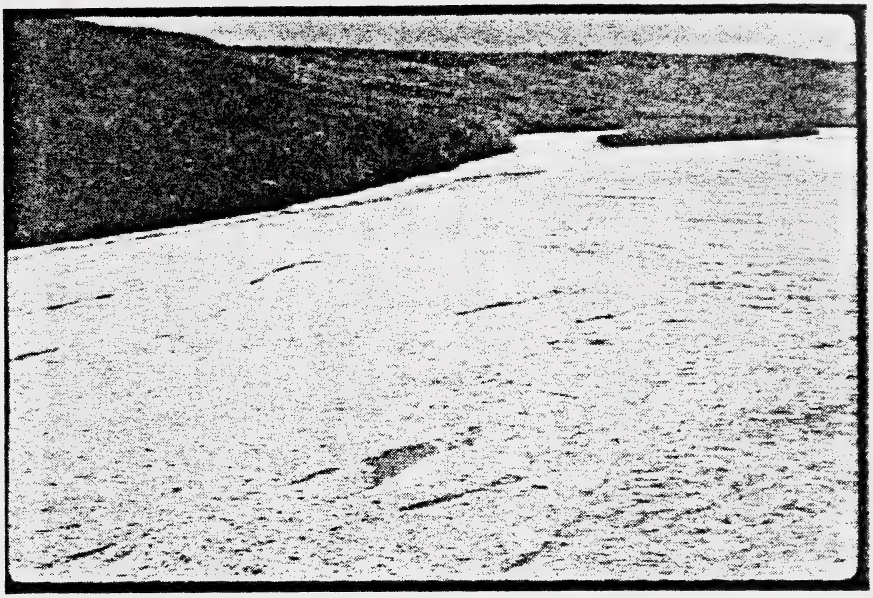

Figure 57. Thin ice cover, approximately one floe thick at the head of the ice jam

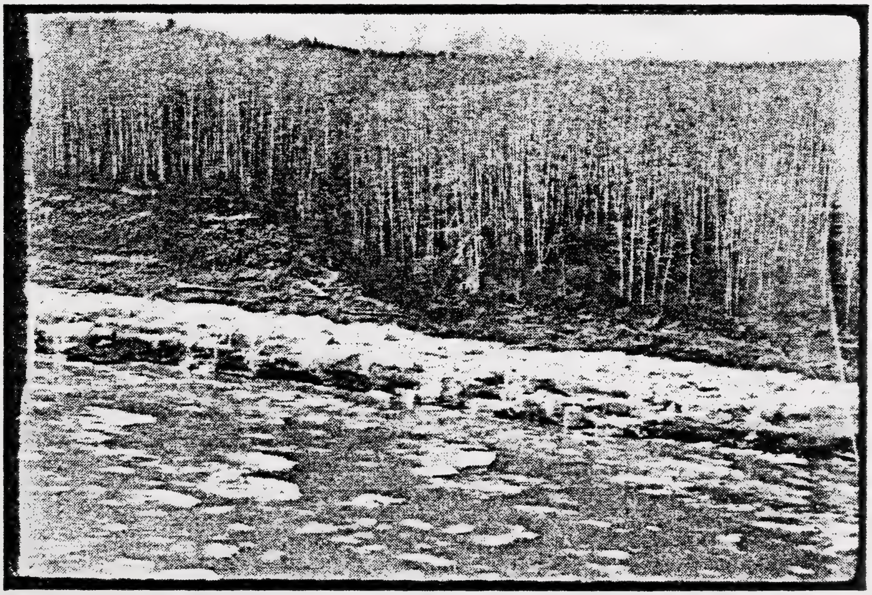

Figure 58. Shear wall in the order of 4 m in thickness upstream of the head of the ice jam

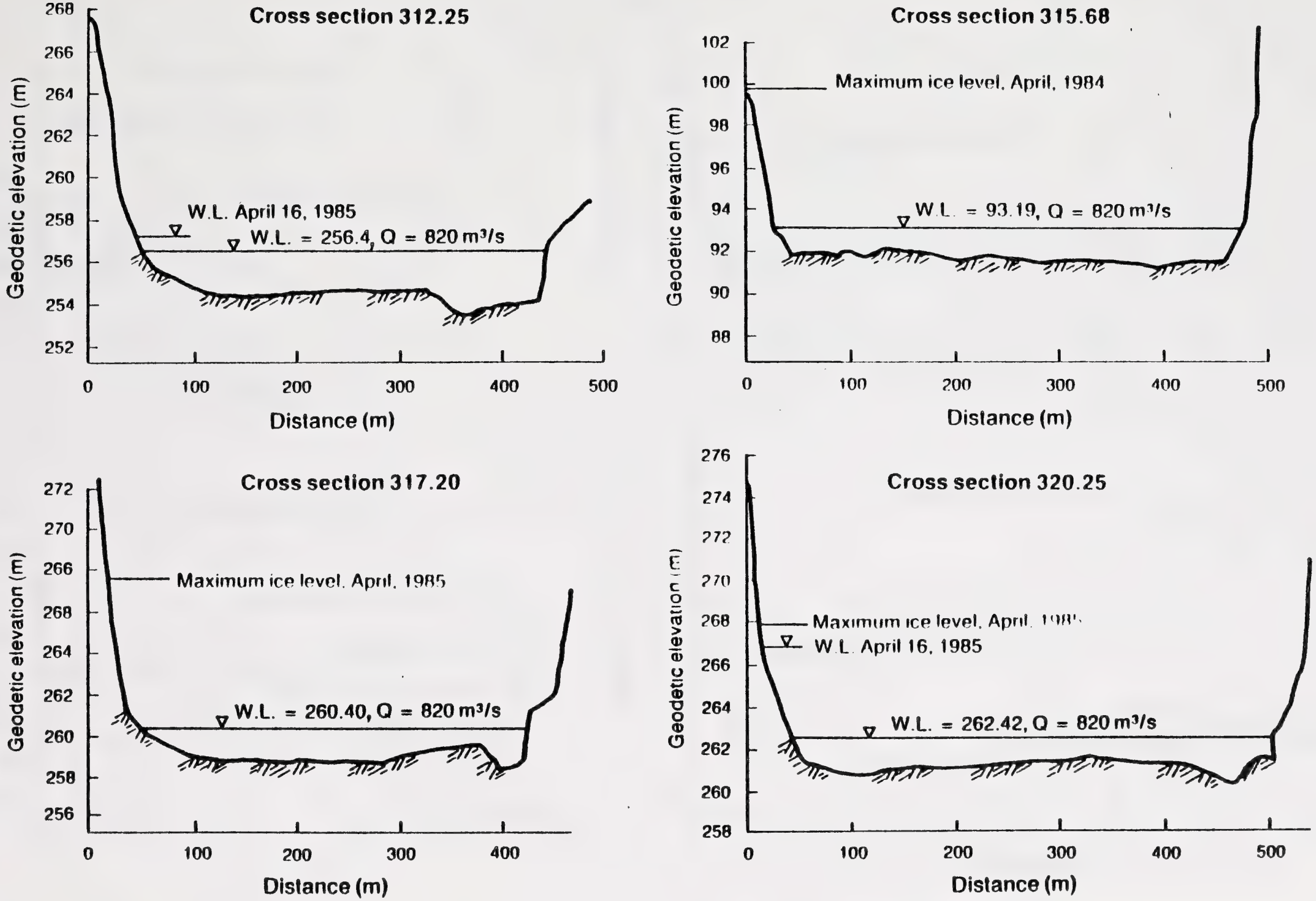

Figure 59a. Surveyed cross sections in the vicinity of the documented ice jam

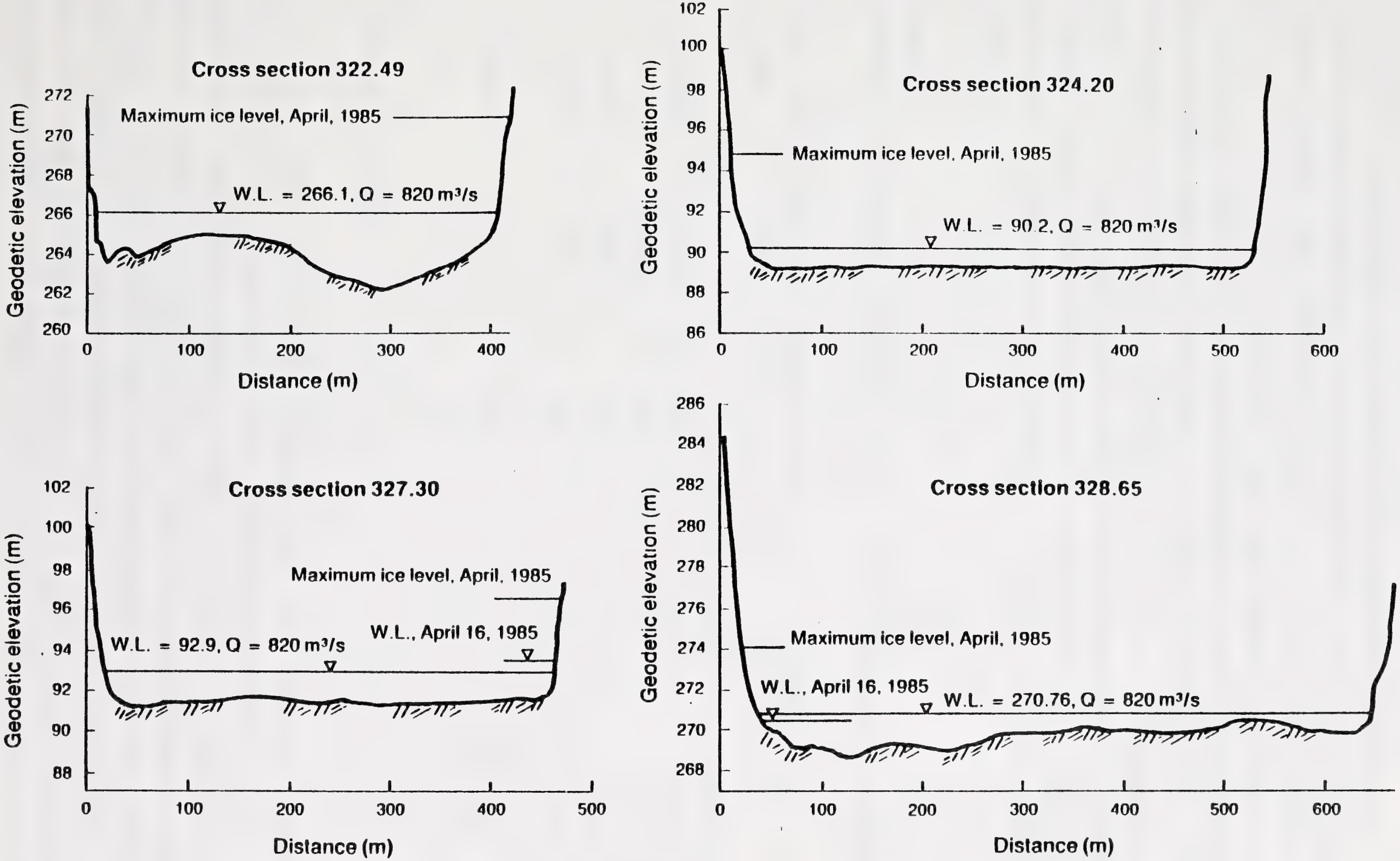

Figure 59b. Surveyed cross sections in the vicinity of the documented ice jam

Table 6 summarizes the geometric characteristics of the ice jam at two different discharges. Only four of the eight cross sections were located within the equilibrium reach of the jam and therefore the characteristics are an average of four measurements. At the formative discharge of 1400 m^3/s (see later discussions) the ice jam attained its maximum mean height of 7.3 m and a top width of 490 m. At a discharge of 620 m^3/s, the height was reduced by 1.3 m to 6.0 m. Presumably this decrease in stage resulted entirely from the reduction in discharge, although it is possible that some of the reduction in stage could be attributed to smoothening and thinning of the jam due to melting of its underside.

Table 6.

Summary of the Geometric Characteristics of the Documented Ice Jam

Cross Section (km)	Bed Level (m)	Channel Width W (m)	Mean Height H (m)	
			Q = 1400 m^3/s	Q = 620 m^3/s
315.68	257.2	500	7.6	6.1
317.20	258.3	450	7.7	6.2
320.25	260.0	530	7.2	6.2
322.49	262.2	440	6.5	5.5
Mean	-	490	7.3	6.0

Discharge Estimates

A continuous record of discharge on the Athabasca River of Fort McMurray was unavailable because the WSC gauge malfunctioned. The malfunction first became apparent at about 15:00 hours on April 14, some 3.5 hours after the formation of the jam upstream of Mountain Rapids. However, the gauge remained operative long enough to indicate that the surge of water from the jam arrived at the WSC gauge at 14:00 hours, and that the stage on the rising limb was increasing at a rate of about 0.00010 m/s from a base gauge height of 3.14 m. This suggests that the

travel time from the jam to the gauge was approximately 2.5 hours. Unfortunately the time to peak cannot be determined from the gauge data because the gauge malfunctioned prior to the peak discharge.

As an alternative means of determining the peak, it is necessary to utilize the water level measurements at the MacEwan Bridge. Although lack of manpower precluded the continuous water level measurement at the bridge, the peak water level at the bridge due to the passage of the surge was measured to be 242.90 m. Using an ice thickness of 1 m and a composite Manning's roughness of 0.022 results in a computed peak discharge at the bridge of 1000 m^3/s. This estimate appears reasonable because the use of the same assumptions and a measured water elevation of 242.33 at the MacEwan Bridge immediately following the profiling of the jam on April 16 results in a computed discharge of 620 m^3/s. This agrees relatively well with the WSC reported discharge of 700 m^3/s downstream of Fort McMurray and of 568 m^3/s at Athabasca for two days earlier.

Combining the data from the WSC gauge and the MacEwan Bridge allows one to define the shape of the rising limb of the hydrograph which resulted from the passage of the surge. At the MacEwan Bridge, the discharge increased from about 320 m^3/s (reduced from the estimated 360 m^3/s for a gauge height to 3.14 m at the WSC gauge by the subtraction of inflow from the Clearwater River) to about 1000 m^3/s over a period of about two hours. The steepness of the rising limb suggests that considerable attention could have occurred between the jam and the bridge and that in fact, the discharge at which the jam stabilized was considerably greater than 1000 m^3/s.

The formative discharge at the jam, was determined by routing trial hydrographs downstream form the jam to the MacEwan Bridge until the adopted hydrograph at the bridge was reproduced with sufficient accuracy. The equations of continuity and momentum, which form the basis of unsteady flow analysis, were solved numerically using an implicit integration scheme outlined by Koutitas (1983). Hydrographs with various peaks but all with a two hour time to rise, where routed

down an ice covered channel assumed to be prismatic, with a width of 450 m, an overall composite Manning's roughness of 0.025, and an average bed slope of 0.00076. Figure 60 illustrates the trial input hydrographs, and compares the output hydrographs to the adopted hydrograph at the MacEwan Bridge.

From figure 60, it appears that the assumptions used in the unsteady flow analysis were not unrealistic. The travel time was reproduced remarkably well and is about 2.5 hours for peak discharges in the order of 1500 m^3/s. If the peak discharge approaches 1000 m^3/s or less, the travel time exceeds three hours. Also, a time to rise of two hours is appropriate for the inflow hydrograph and reproduces the observed hydrograph as long as the peak discharge is at least 1400 m^3/s. Finally, an input hydrograph with a peak discharge of 1400 m^3/s seems to best match the observed outflow peak of 1000 m^3/s.

It must be cautioned, that the unsteady flow analysis assumed a prismatic channel with a constant cross sectional geometry and a constant slope. This would result in lower attenuations of the peak discharge than a natural, irregular channel. Therefore the adopted formative discharge at the jam of 1400 m^3/s is probably a minimum value and it could easily approach 1600 m^3/s if a more detailed analysis was done. However, for the purposes of the stability analysis in the following section, the adopted values for the discharge at the time of the jam formation and at the time of survey are 1400 m^3/s and 620 m^3/s respectively.

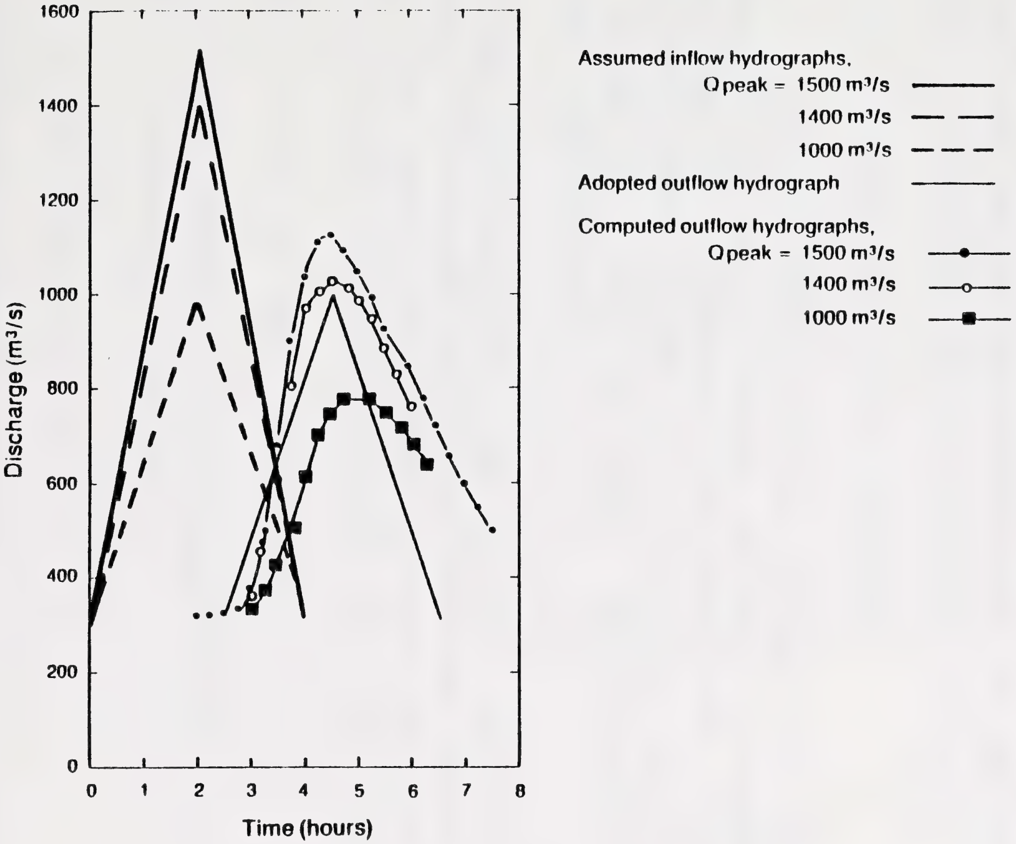

Figure 60. Estimates of the formative discharge of the ice jam upstream of Mountain Rapids

Hydraulic Characteristics and Stability Analysis

Pariset et al. (1966) and Uzuner and Kennedy (1974) developed theories to predict the thickness of the equilibrium portion of a "wide channel" jam formed by internal collapse. Beltaos (1978) outlined the similarity of both approaches and suggested that if the porosity of the ice cover was the same above and below the water level, the stability equation for a "wide channel" jam could be given by

$$[3] \qquad \mu\rho_i(1-S_i)gt^2/2 = [W(\tau_i + \rho_i gSt)/2]-C_i t$$

where μ is the dimensionless coefficient related to the internal friction of the ice cover, ρ_i the density of the ice, S_i the specific gravity of ice, t the jam thickness, W the channel width, τ_i the shear on the underside of the ice cover, g the acceleration of gravity, S the water surface slope, and C_i the cohesion (can be assumed to be negligible) of the ice cover.

The equilibrium stage H of a simple ice jam is composed of the thickness of the ice and the depth of flow of water under the ice. This depth of flow is equal to the sum of the flow depth R_i associated with the ice cover and the flow depth R_b associated with the bed. Thus,

$$[3] \qquad H = R_i + R_b + S_i t$$

and considering the equilibrium of forces between the bed, the ice and the flow in a streamwise direction, then

$$[4] \qquad \tau_i = \rho gSR_i$$

where ρ is the density of water.

Given a discharge Q at the time when the equilibrium thickness of the jam was established, the flow under the jam can be described by

$$[5] \qquad Q = (1/n_o)(1/2)^{2/3}(H-S_i t)^{5/3}\ WS^{1/2}$$

where n_o is the composite roughness given by

$$[6] \qquad n_o = ((n_i{}^{3/2}+n_b{}^{3/2})/2)^{2/3}$$

where n_i and n_b are the roughness of the ice cover and channel respectively.

Assuming that the average velocities in the flow area associated with the ice cover and the bed are equal, then

$$[7] \qquad R_i/R_b = (n_i/n_b)^{2/3}$$

Following Beltaos (1978), and combining equations [3] and [4] produces one equation with μ, τ_i, and R_i as the three unknowns. Combining equations [2], [3], [5] and [6] produces another equation with t and R_i as unknowns. This results in an indeterminate set of equations with three unknowns and two equations. The only way to close the system is by directly measuring the thickness or the roughness of the jam. To date, this has proven impossible at Fort McMurray.

Fortunately, the documented jam remained in place for a long period of time and two profiles at two greatly different discharges were established. Assuming no large changes in the ice thickness and roughness between April 14 and April 16, and that the change in stage was due only to change in discharge, it was possible to independently determine the thickness of the jam and the composite roughness as suggested by Andres (1980). Equation [5] was written for both days and solved simultaneously for t and n_o. Then, knowing values of n_b, the bed roughness, equation [6] was used to determine n_i.

Table 7 shows the results of the calculations for various formative discharges greater than 1400 m^3/s. It is evident from the table that regardless of the discharge chosen, the thickness of the jam exceeds 4 m, the thickness of the observed shear walls. For discharges as large as 1600 m^3/s, the thickness is realistic. However, for all three discharges the roughness of the ice cover appears to be lower than the

0.070 value observed by Andres and Doyle (1984) and somewhat confirmed by Andres and Rickert (1985). In fact, the computed roughness suggest that the formative discharge probably did not get much beyond 1400 m^3/s, because the roughness rapidly decreases to unreasonably low values if the formative discharge increases beyond 1400 m^3/s.

Table 7.

Trial Estimates of the Thickness and Roughness of the Documented Ice Jam

Trial Formative Discharge (m^3/s)	Thickness (m)	Ice Jam Roughness ($s/m^{1/3}$)
1400	4.3	0.063
1500	4.5	0.048
1600	4.7	0.036

Table 8 summarizes the relevant hydraulic characteristics of the ice jam for the adopted formative discharge of 1400 m^3/s. The roughness of the ice cover was determined to be 0.063, which is lower than one might expect from previous evidence. The coefficient of internal friction was computed to be 1.82, higher than previously defined. If the roughness is increased to previously reported values, the computed ice thickness would decrease and the coefficient of internal friction would increase to even larger values.

Table 8.

Summary of the Measured and Computed Ice Jam Characteristics

	Date	
	April 14	April 16
Discharge, Q (m^3/s)	1400	620
Slope, S (m/m)	0.00076	0.00076
Width, W (m)	490	490
Jam Height, H (m)	7.3	6.0
Jam Thickness, t (m)	4.3	4.3
Composite roughness, n_o ($s/m^{1/3}$)	0.046	0.046
Bed roughness, n_o ($s/m^{1/3}$)	0.025	0.025
Ice roughness, n_i ($s/m^{1/3}$)	0.063	0.063
Hydraulic roughness due to bed, R_b (m)	0.7	0.4
Hydraulic radius due to ice, R_i (m)	2.7	1.7
Shear stress on ice cover τ_i (P_a)	20.1	12.7
Coefficient of internal friction, μ	1.82	-

SUMMARY AND CONCLUSIONS

Breakup Observations

The potential for an above average runoff due to the high snow pack was reduced considerably by a long drawn out melt period with the warming trend punctuated by numerous cold spells. Breakup in the Little Paddle and Paddle River basins began as early as March 10 after only 5 C°-days of melt at Campsie. Only a small amount of melt was apparent at the snow pillow and yet this seemed to have a significant impact on the flow in the rivers, particularly the Little Paddle River. Either the snow pillow is not an effective indicator of the melt process or even small amounts of melt early in the spring generates significant runoff.

Breakup on the Paddle River at Barrhead was not completed until April 2, and the Pembina River at Jarvie followed on April 12, although

many reaches on the Pembina River had undergone breakup by April 9. On a whole, the Pembina River broke up in an over-mature condition well after the peak stages had occurred. Obviously, even with the high snow pack, the temperatures simply were insufficient to generate enough runoff to create a spectacular breakup.

Breakup on the Athabasca River was fragmented. On April 6, after 35 C°-days of melt, the Athabasca River downstream of the Pembina River was affected somewhat by outflows of ice and water from the Pembina River. By April 10, after 50 C°-days of melt, considerable impact was apparent at Hondo and upstream of Athabasca. After about 70 C°-days of melt, breakup was well underway upstream at the Town. The breakup at Athabasca proved to be uneventful, partly because the ice upstream of km 740 was isolated and played no part in the breakup process.

Between Athabasca and Fort McMurray, the Athabasca River broke up in distinct sections. The ice downstream of Rapides du Joli Fou went out first (April 14), ultimately producing a jam upstream of Mountain Rapids. The ice upstream of Rapides du Joli Fou never did get downstream but was trapped behind a jam at the rapids. Finally, the ice below Mountain Rapids went out, removing the ice at Fort McMurray on April 18. However, by that time, the ice downstream of the City was so deteriorated that the breakup was uneventful.

It is interesting that after March 20, the melt at Fort McMurray was considerably less than the melt at Slave Lake. In early April, Slave Lake was about five days ahead of Fort McMurray and the melt at Fort McMurray did not catch up by the time breakup was over. However, even with the entrapment all the ice upstream of Rapides du Joli Fou, the ice cover upstream of Fort McMurray broke up two days after the ice cover at Athabasca. This tends to illustrate the effect the rapid sections have on accelerating the breakup process. That is, it takes about three days less deterioration of the ice cover to initiate breakup (at more or less equal discharge) in the rapid sections.

A number of conditions contributed to the uneventful breakup at Fort

McMurray. All the ice upstream of Rapides du Joli Fou was excluded from the ice run upstream of the City. This tended to reduce the intensity of the ice run and hence allowed the ice to stall and form a jam. Even after the jam formed, there was still potential for a serious jam at Fort McMurray if the jam would have been dislodged. This could only have been initiated by a significant increase in discharge from upstream. Fortunately this did not develop because the long drawn out melt seemed to limit the runoff. As a result, the jam underwent in situ deterioration and the large mass of ice necessary to create a dangerous jam at Fort McMurray never materialized.

This year, four flights and some limited ground observations were undertaken to observe breakup. Unfortunately, the crucial initial period of breakup between April 6-12 was not observed. Therefore, the breakup between Smith and Athabasca was not properly characterized and there still remain some questions regarding how the ice cover goes out in this reach. It seemed apparent that an observation flight was required every two days during the middle stages of breakup. Once this practice was adopted (after April 11) the breakup was better documented especially when daily flights were made as the process accelerated.

Experimental Ice Station

The experimental ice station was a limited success in that it successfully transmitted indications of ice movement in real time. Unfortunately it probably cannot give sufficient advance warning for Fort McMurray to mobilize its flood fighting personnel without considerable additional observations. First, the station can only record ice movement up to 100 m, beyond which it would simply indicate an abnormality. On the Athabasca River, sporadic ice movements of 100 m are not uncommon, especially in the vicinity of rapid sections, and can occur one to two weeks before the real breakup occurs. Second, if the station transmits movement in excess of 100 m it very well could be due to the passage of an ice run. At this point, Fort McMurray could be in flood in two to four hours if an ice jam forms downstream of the mouth of the Clearwater River, due to the ice run. On the other hand, the run

may stall upstream of Fort McMurray, as it did this year, and breakup could still be one week away. It is apparent that in its present form the ice station would prove successful within a very narrow range of probabilities.

There are a number of things which can be done to improve the performance of the system. First, it is recommended that water levels are also measured and transmitted. If the water level can be measured to at least ±0.3 m one can easily get an indication if the ice movement is the result of real breakup or simply the pre-breakup ice shifting which normally occurs. The ice station should be located further upstream in an area which would allow sufficient time for Fort McMurray to react should an ice run be sensed. At present, the most favourable location appears to be near the mouth of the House River. This reach appears to trigger the ice run downstream and once this reach goes out the run is well on its way downstream. However, it recommended that additional observations of future breakups are made to confirm this notion.

It must be cautioned, however, that regardless of the sophistication of the monitoring system, there is always the possibility that breakup at Fort McMurray can be forecasted up to one week too early, simply because the run can stall within 10 to 15 kilometres of Fort McMurray for up to one week without affecting the ice cover at Fort McMurray.

Ice Jam Characteristics

During the 1985 breakup a significant jam formed upstream of Mountain Rapids. The jam, whose toe was grounded, achieved a length of 14 km, an average height of 7.3 m, and an average thickness in excess of 4 m. The discharge at which the jam formed was estimated to be about 1400 m^3/s.

Jam profiles at two different discharges allowed a direct computation of both the roughness and the thickness of the jam. These proved to be 0.063 $s/m^{1/3}$ and 4.3 m respectively. The dimensionless coefficient

of internal friction of the jam was calculated to be 1.8. This is considerably larger than many previous estimates, especially in light of the low hydraulic roughness of the jam. It may be possible that there was grounding at intermittent locations throughout the body of the jam and therefore all the stress did not have to be carried by the ice itself. This would result in a thinner cover than normal, and ultimately a greater apparent internal strength.

Although the two profiles allowed an independent estimate of both the roughness and thickness, it would still be advantageous to attempt to get actual ice thicknesses by some remote technique. The airborne impulse radar probably offers the most potential. It is recommended that experiments be undertaken to determine its utility. It is suggested that the entire length of a jam and some cross sections be surveyed to establish the three dimensional nature of the ice accumulation.

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